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**The development of an evidenced-based submaximal cycle test  
designed to monitor and predict cycling performance**

***The Lamberts and Lambert Submaximal Cycle Test (LSCT)***

Paper-based thesis presented for the Degree of

**Doctor of Philosophy**

**in**

**EXERCISE SCIENCE**

at the

University of Cape Town

UCT/MRC Research Unit for Exercise Science and Sports Medicine  
Department of Human Biology, Faculty of Health Sciences

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# **DECLARATION**

I, Robert Patrick Lamberts, do hereby declare that the research presented in this thesis is based on 6 articles of which 5 articles (chapter 2,3,4,5 and 6) have been published or accepted for publication and 1 article (chapter 7) is submitted for publication. To meet the stylistic requirements of a thesis, the format of the published papers have been adjusted accordingly and abbreviations of units and terms standardised throughout. The role which I fulfilled within each of the research projects and publications is presented below.

## **Chapter 2.**

**R.P. Lamberts** and M.I. Lambert (2009) *Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. Journal of Strength and Conditioning Research*, 23(3): 1005-1010.

I drafted the research proposal, successfully applied for ethical clearance, and collected all the data. During the testing period I received support from Dr. R. Arendse and intellectual advice from J. Durandt. I analysed all data and drafted the current published manuscript. Apart from the normal guidance from my supervisor M.I. Lambert, I did not receive any other assistance.

## **Chapter 3.**

**R.P. Lamberts**, J. Swart, T.D. Noakes and M.I. Lambert (2009) *Changes in heart rate recovery after high intensity training in well-trained cyclists. European Journal of Applied Physiology*, 5: 705-713

I drafted the research proposal and assisted in obtaining ethical clearance for this research project. The data for this research project was captured with assistance of Dr. J Swart. I personally analysed all data and drafted the current published manuscript. Apart from the normal guidance from my supervisors M.I. Lambert and T.D. Noakes, I did not receive any other assistance.

#### **Chapter 4.**

**R.P. Lamberts, J. Swart, B. Capostagno, T.D. Noakes and M.I. Lambert (2009)** *Heart rate recovery as a guide to monitor fatigue and predict performance parameters. Scandinavian journal of Medicine and Science in Sports (Epub; ahead of publ.)*

I drafted the research proposal and successfully applied for ethical clearance. The data for this research project was captured with assistance of Dr. J Swart, while B Caspostagno assisted with interpreting the data. I personally analysed all data and drafted the accepted manuscript for publication. Apart from the normal guidance from my supervisors M.I. Lambert and T.D. Noakes, I did not receive any other assistance.

#### **Chapter 5.**

**R.P. Lamberts, J. Swart, R. Woolrich, T.D. Noakes and M.I. Lambert (2009)** *Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status. International SportsMed Journal 10(1): 33-44*

I drafted the research proposal, applied successfully for ethical clearance. The data for this research project was captured with assistance of Dr. J Swart and R. Woolrich. I personally analysed all data and drafted the current published manuscript. Apart from the normal guidance from my supervisors M.I. Lambert and T.D. Noakes, I did not receive any other assistance.

#### **Chapter 6.**

**R.P. Lamberts J. Swart, T.D. Noakes, M.I. Lambert.** *A novel submaximal cycle test to monitor fatigue and predict cycling performance. British Journal of Sports Medicine, July 2009 (Epub: ahead of publ.)*

I drafted the research proposal, applied successfully for ethical clearance. The data for this research project was captured with assistance of Dr. J Swart. I personally analysed all data and drafted the accepted manuscript for publication. Apart from the normal guidance from my supervisors M.I. Lambert and T.D. Noakes, I did not receive any other assistance.

## **Chapter 7.**

**R.P. Lamberts, G.J. Rietjens, H.H. Tijdkink, T.D. Noakes, M.I. Lambert.** *Measuring submaximal performance parameters to monitor fatigue and predict cycling performance: a case study of a world-class cyclo-cross cyclist.* European Journal of Applied Physiology, November 2009 (Epub: ahead of publ.)

I drafted the research proposal and successfully applied for ethical clearance. The data for this research project was captured with assistance of Dr. G.J. Rietjens and H.H. Tijdkink. I personally analysed all data and drafted the current submitted manuscript for publication. Apart from the normal guidance from my supervisors M.I. Lambert and T.D. Noakes, I did not receive any other assistance.

All co-authors have granted their permission to Robert Patrick Lamberts for using the above mentioned work for his degree of Doctor of Philosophy in Exercise Science at the University of Cape Town, UCT/MRC Research Unit for Exercise Science and Sports Medicine, Department of Human Biology, Faculty of Health Sciences. In addition, all scientific journals have been notified that the above mentioned publications are being used as part of the degree of Doctor of Philosophy in Exercise Science at the University of Cape Town.

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This publication based thesis is presented for examination in fulfilment of the requirements for the degree of Doctor of Philosophy in Exercise Science

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# Chapter 1

**A brief history of submaximal testing**

An introduction

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## INTRODUCTION

Performing at the highest level in professional sports is dependent on finding the optimal balance between the training workload and the recovery period, so that training effects and adaptations are maximised. In an attempt to maintain this fine balance, it is important to monitor the training load, changes in performance and symptoms of fatigue which may develop when this balance is disturbed. Perhaps the biggest challenge is to monitor these changes on a regular basis so that intervention can be implemented as soon as there is evidence that the balance is disturbed. Tests that are able to predict cycling performance, for example a peak power output (PPO) test or a 40-km time trial (40-km TT), require a maximal or near maximal exertion. Therefore these tests are not performed on a regular basis as they may interfere with the prescribed training or racing programme of an elite cyclist (Jeukendrup 2002; Lucia et al. 2000). It follows therefore that a less exhaustive submaximal test should rather be used for ongoing regular monitoring of well-trained and elite cyclists (Jeukendrup 2002). However, as a submaximal test only *predicts* performance, the accuracy of this prediction will influence how useful the test may be as a monitoring tool for already well-trained or elite cyclists. To understand the current status of performance testing, it is important to know the origins of exercise physiology and trace the development of submaximal tests which were designed to predict performance.

### ***A brief history of performance testing***

When sport became more professional in the early 1700's and research in the field of physiology was gaining momentum, it was logical that the interest in exercise physiology also started to develop. An important contributor in this process was a Frenchman Antoine Laurent Lavoisier (1743-1794), who was one of the first researchers to conduct and document exercise physiology studies (Duveen and Klickstein 1955). Although Lavoisier conducted the pioneering research, it was his wife Marie-Anne Pierette Paulze who documented all the experiments to ensure that his work was published. In the late 1800's the German Eduard Friedrich Wilhelm Pflüger (1829-1910) contributed substantially to knowledge in respiratory physiology and electrophysiology. This work subsequently formed the basis for the development of electromyography. In addition he founded the '*Archive für die gesamte*

*Physiologie* in 1868. This journal has developed into one of the current prominent journals publishing research on exercise physiology and sports medicine (Pflügers Archives - European Journal of Physiology). One of Pflüger's students, Nathan Zuntz (1847-1920), became a professor at the *Landwirtschaftliche Hochschule* in Berlin. He led a research group which conducted innovative research on exercise metabolism, nutrition and respiratory responses (Gunga and Kirsch 1995a; Gunga and Kirsch 1995b). This group developed the '*Laufband*', the predecessor of the treadmill, and the '*Zuntz-Geppert respiratory apparatus*' which is the predecessor of modern metabolic gas analyzers.

A similar device, which also measures oxygen consumption during exercise, was developed by Claude Gordon Douglas. This device, known as the Douglas bag, was able to capture the expired air of a subject during exercise (Douglas 1911). After the bout of exercise the volume and composition of the exhaled air could be analyzed for the determination of oxygen consumption, carbon dioxide production and metabolic rate. This research methodology was frequently used by Archibald Vivian Hill (1886-1977) to study questions in the field of exercise physiology and medicine.

This researcher, together with Otto Fritz Meyerhof, was awarded the Nobel Prize in 1922 for their contributions to the field of physiology and medicine. Even today there is still a lively debate about how this physiological model explains maximal exercise capacity (Bassett, Jr. and Howley 1997; Ekblom 2009; Meeusen et al. 2007; Noakes et al. 2001; Noakes and Marino 2009; Wagner 2000). It can be concluded with confidence that this research was the catalyst for laboratory testing of elite athletes, and has made a substantial contribution to the understanding of high performance physiology (Hill and Lupton 1923).

As a direct consequence of Hill's work, performance testing in men started to gain popularity from the early 1900's. However, it was only in the 1960's that a Swedish PhD Student, Per-Olaf Åstrand, started conducting maximal performance tests in females (Åstrand 1952). Prior to this it was regarded as dangerous and socially unethical for females to undergo maximal exercise. The research of Åstrand showed that a maximal performance test might not always be the most appropriate test for a subject (male or female), as it could interfere with health in certain clinical

populations, and in the context of athletes, would interfere with their normal training habits.

### ***Submaximal performance testing***

As a consequence of the limitations of maximal performance testing, Åstrand and Ryhming developed a submaximal cycle test to predict  $VO_{2max}$  as a measurement of “aerobic fitness” (Åstrand and Ryhming 1954). The test, known as the Åstrand test, is currently widely used. A similar submaximal cycle test, developed in the 1970’s, also predicts  $VO_{2max}$  by estimating the workload coinciding with a heart rate of 170 beats per minute. This test, known as the Physical Work Capacity (PWC 170) test, is still used regularly (Haber et al. 1976; Trudeau et al. 2003).

As the Åstrand test gained popularity in the 1960’s, researchers also started to develop submaximal walking and running tests. One of the first submaximal running tests was developed by Kenneth Cooper in 1968. In this test subjects are asked to cover as much distance as possible within 12 minutes, and  $VO_{2max}$  is then predicted from the completed distance (Cooper 1968). This test was a catalyst for the development of a variety of submaximal walking and running tests which were designed to accommodate the specific needs of special populations. Examples of these tests are the six-minute walk test for cardiac and respiratory patients (Butland *et al.* 1982), and the shuttle walk test for respiratory patients and patients with chronic obstructive pulmonary disease (Singh *et al.* 1992). To accommodate subjects with a relatively low exercise capacity, such as elderly people or people with severe obesity, Kline *et al.* (1987) and Laukkanen *et al.* (1992) developed the Rockport Fitness Walk and UKK walk test respectively.

In contrast to the development and specialisation of submaximal running tests, submaximal cycle tests have not evolved further beyond the Åstrand test and the PWC 170 test. However, as explained earlier, a limitation of both these tests when applied to highly trained athletes is that both tests predict  $VO_{2max}$ . While the  $VO_{2max}$  of highly trained athletes is higher than that of lesser trained athletes (Arts and Kuipers 1994; Lucia et al. 2002b), the practical application of this measurement to monitor changes over time in well-trained and elite cyclists is questionable. For example, there is evidence that  $VO_{2max}$  varies by over 25% in professional cyclists (Lucia *et al.*

2002; Mujika and Padilla 2001), and has shown to have a limited relationship with athletic ability (Lucia et al. 2002a; Noakes 2008). In addition, a study by Lucia *et al.* (2002) showed that  $\text{VO}_{2\text{max}}$  in professional road cyclists only changes by 1.1% between pre-competition and in-competition, while the current typical error of measurement (TEM) of  $\text{VO}_{2\text{max}}$  is about 2 to 3% (Paton and Hopkins 2006). Despite these limitations,  $\text{VO}_{2\text{max}}$  is still regarded, in some quarters, as being an important measurement for predicting fitness in well-trained and elite athletes.

### ***The development of a novel submaximal cycle test***

The limitations of applying  $\text{VO}_{2\text{max}}$  to monitoring the response to training have been clearly exposed. As discussed earlier, finding the optimal balance between training load and recovery is a fundamental requirement for achieving peak performance. When this balance is disrupted by either a training load which is too high and or a recovery period which is insufficient, a subject will start to accumulate fatigue. This will initially manifest as acute fatigue which can lead to a state of functional overreaching (Meeusen *et al.* 2006). This state can cause a stagnation or decrement in performance, however is sometimes used as a training technique to improve performance (Halsen et al. 2003). The goal of this approach is to reach 'super-compensation' in the following recovery period, which is associated with enhanced performance (Meeusen *et al.* 2006). However when imbalance persists over a longer period, the accumulated fatigue becomes chronic with more exacerbated and longer lasting effects on performance (non-functional overreaching). This state can even progress into a more serious condition, known as the overtraining syndrome, which has been associated with severe impairment in performance and recovery times ranging from months to up to over a year (Meeusen *et al.* 2006).

Although this scenario may only seem relevant for well-trained athletes, it is also applicable to certain population groups who are encouraged to lower their risk of disease by increasing their physical activity. Maintaining the balance between training and recovery in these patient groups is as important for them as it is for well-trained athletes. In the case of the special population groups, for example in cardiac patients, it prevents them from developing serious health consequences, and in the case of the well-trained athlete it prevents them from reaching their optimal peak

performance.

Monitoring this balance however is complex as both factors (training load and recovery) are influenced by multiple factors. For example, training load is influenced by the intensity, volume, frequency and duration of exercise (Jeukendrup 2002). The recovery is determined by less quantifiable factors such as stress, sleeping patterns, nutrition and psychological and sociological well-being (Jeukendrup 2002; Kenttä and Hassmen 1998). With it being so complex, it seems unrealistic to expect one single parameter to detect or indicate an imbalance between training load and recovery with any accuracy (Borresen and Lambert 2007).

### ***Incidence of overreaching and overtraining***

Due to the different definitions for overtraining and overreaching (Halsen and Jeukendrup 2004; Lehmann et al. 1997; Robson 2003; Roelands et al. 2008; Silva 2009; Tenenbaum et al. 2003a; Tenenbaum et al. 2003b; Urhausen 2001) it is hard to accurately quantify the incidence of overreaching and overtraining. In addition, the preference for certain terminology between USA and Europe seem to further complicate this. For example, the term 'staleness' or 'stale' is often used in the USA and seems to refer to a state of overtraining or overtraining syndrome.

Lehman et al (1997) has estimated that between 20 to 60% of athletes will at least once during their career develop a state of overtraining. Although this percentage will be substantially lower on a yearly basis, Halsen and Jeukendrup still expected the incidence of overtraining to be relatively high (Halsen and Jeukendrup 2004). Research on competitive swimmers has shown that about 5-10% of the swimmers were 'stale' (Morgan et al. 1987; O'Connor et al. 1989; Raglin and Morgan 1994). Associated with this 'staleness' were increased ratings of fatigue, while subjects indicated a decreased performance. Objective measurements of changes in performance were however only measured in one study on swimmers (Hooper et al. 1997).

A study of 257 athletes of the British National Teams and/or Olympic squad showed



an incidence of 38 cases (15%) over a 12 month period in which a state of 'overtraining' was diagnosed (Koutedakis and Sharp 1998). Although the incidence was slightly higher in males (17%) than in females (11%), there was an even distribution of these incidences within the different sports. Also, in this study no objective measurements were performed to confirm the anecdotal claim of a decrease in performance with increased ratings of fatigue.

### ***Power output and fatigue***

As peak power output has shown to correlate well with cycling performance (Arts and Kuipers 1994; Bentley et al. 2001; Faria et al. 2005; Hawley and Noakes 1992) and performance seems to be effected as fatigue accumulates, the measurement of changes in power seem to be important. This concept was adopted in a protocol designed to distinguish between normal training status and an overreached status (Meeusen et al. 2004). The protocol used a double peak power output performance test with each test being separated by 4 hours. When subjects were overreached, a larger decrement in peak power output was observed between the 2 tests (Meeusen et al. 2004).

Although this technique has the potential to confirm the status of an overreached or overtrained athlete, the physically exhausting nature of the test precludes it from being used on a weekly basis for monitoring purposes. Therefore a submaximal cycle test, which is able to monitor changes in power and be administered on a weekly basis, would be of importance to a cyclist, sports scientist and coach alike.

### ***Overall wellbeing and ratings of perceived exertion***

In contrast to the lack of actual performance tests to confirm a state of overtraining, most studies do use questionnaires to confirm a general state of fatigue. A frequently used and widely excepted questionnaire to assess psychological well-being is the Profile of Mood Status (POMS) questionnaire (McNair et al. 1971). Although this questionnaire measures aspects of tension, depression, anger, vigor, fatigue and confusion to assess the general mood status, it has shown mixed results to quantify an overreaching status (Halsen et al. 2002; Martin et al. 2000; Nederhof et al. 2007; Rietjens et al. 2005; Uusitalo 2001). A possible explanation for this might be that this general questionnaire is not sufficiently sport specific.

A more specific questionnaire designed to assess the sport specific stress of training is the Daily Analysis of Life Demands for Athletes (DALDA) questionnaire (Rushall 1990). This questionnaire has evolved into its current format after being validated and tested for reliability. Halson et al. (2002) showed a change in DALDA scores after 2 weeks of high intensity training. These scores were associated with the accumulation of fatigue and a decrease in peak power output and 40km time trial time (Halson et al. 2002). Although these data suggest that this is possibly a better questionnaire for monitoring training stress in athletes compared to the POMS, the DALDA is rarely used in overtraining studies.

A more direct way of assessing an athlete's well-being can be performed by using a 6-20 Borg Scale (Borg 1970) or the subsequently developed 10 point scale (0-10) Borg Scale (Borg 1982). This method is normally used during or directly after a performance test when a subject rates his/her overall rate of perceived exertion on a 6-20 or 0-10 scale respectively. One of the first studies that used RPE as a monitoring tool, showed that during steady state running the athlete's RPE (6-20 scale) correlated well with average heart rate during that training session (Robinson et al. 1991). Recent studies (Rietjens et al. 2005; Uusitalo 2001) however, have also proposed that increased RPE levels at the same constant workload can play an important role in detecting a state of overreaching.

### ***Heart rate recovery***

The regulation of the autonomic nervous system has also shown potential for detecting the imbalance between training and recovery because the autonomic nervous system is interlinked with both physiological and psychological systems and has been able to predict mortality in healthy subjects (Cole *et al.* 1999). The autonomic nervous system is composed of the parasympathetic and sympathetic nervous systems. Whereas the parasympathetic nervous system is mainly active during resting conditions, the sympathetic nervous system becomes active with exercise or a fight-or-fright response (Brooks *et al.* 2005). Therefore activation of the sympathetic nervous system and withdrawal of the parasympathetic nervous system can be observed with increasing exercise intensity. In contrast, heart rate recovery after the cessation of exercise is regulated by parasympathetic reactivation and

sympathetic withdrawal (Borresen and Lambert 2007; Bunc et al. 1988).

Two measurements, heart rate recovery and heart rate variability have been associated with the regulation of the autonomic nervous system (Borresen and Lambert 2007; Buchheit *et al.* 2007b; Buchheit and Gindre 2006; Bunc *et al.* 1988; Kaikkonen *et al.* 2008; Lamberts *et al.* 2004; Seiler *et al.* 2007; Shetler *et al.* 2001). Support for the measurement of heart rate recovery can be found in studies which have shown a change in heart rate recovery with a change in training status (Buchheit *et al.* 2007a; Buchheit *et al.* 2008; Otsuki *et al.* 2007; Sugawara *et al.* 2001; Yamamoto *et al.* 2001). In addition, a recent study showed a decrease in heart rate recovery after a sudden increase in training load (55%) which was possibly a result of accumulating fatigue (Borresen and Lambert, 2007).

The measurement of heart rate variability also reflects the functioning of the autonomic nervous system. Although this method is based on sound theoretical principles, there is still much debate on how to measure and analyse these data. This possibly contributes to the inconclusive results that are found in studies which have measured heart rate variability (Aubert *et al.* 2003;; Tulppo *et al.* 1998). In addition age (Carter and Jeukendrup 2002; Levy et al. 1998; Tulppo et al. 1998), respiration (Tulppo et al. 1998) and temperature (Carter and Jeukendrup 2002) influence the measurement of heart rate variability. Recent studies suggest Buchheit (2007b; 2008) that the heart rate variability and heart rate recovery reflect different adaptations of the autonomic nervous system in a response to a change in training status. Where the indices of heart rate variability seem to reflect a more long term modulation of the autonomic nervous system, the indices of heart rate recovery seem to be more responsive to recently applied training loads (Buchheit *et al.* 2007b; Buchheit *et al.* 2008).

Based on the knowledge that indices of heart rate recovery are more sensitive measures of small changes over time, the measurement of heart rate recovery seems to be a more appropriate method for monitoring small changes as part of an ongoing monitoring system (Borresen and Lambert 2008).

### ***Aim and layout of the thesis***

The development of technical devices such as cycle ergometers and heart rate

monitors has provided the opportunity to measure a wider range of variables simultaneously. This offers the potential to overcome the limitation of being unable to accurately detect symptoms of an imbalance between training and recovery as a result of being able to measure only one marker. Therefore the aim of this thesis was, to develop a novel, evidence-based submaximal cycle test with sufficient precision to be able to monitor and predict cycling performance. In an attempt to make the submaximal test both evidenced-based and practically useable for high performance cyclists, the new submaximal test had to fulfil the following criteria:

- should be non-invasive and submaximal
- should not interfere with the subject's normal training or racing habits
- should be able to use the test for warming up before a performance test, training session, or racing event
- should have a maximal duration of a 'normal' warming up period (about 20 minutes)
- should be able to measure both objective and subjective data simultaneously
- have sufficient sensitivity to be able to reflect meaningful changes in performance parameters

At the onset of the project the submaximal cycle test was named the '*Lamberts and Lambert submaximal cycle test*' or in the abbreviated forms '*LSCT*'. The overall goal of this thesis was to develop the LSCT to meet the criteria described above. To accomplish this goal 6 studies were designed to answer different research questions relevant to the points above. Each question contributes in some way to the criteria outlined above. These questions are summarized in Table 1.1.

**Table 1.1** Descriptive overview of the six initial studies for the development of the LSCT.

<b>Study</b>	<b>Title and research aim</b>
<u>Study 1</u> (Chapter 2):	<b>Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training</b>  <i>Research aim: The aim of the study was to determine the within subject day-to-day variation of submaximal and recovery heart rate in subjects who reached different exercise intensities.</i>
<u>Study 2</u> (Chapter 3):	<b>Changes in heart rate recovery after high intensity training in well-trained cyclists</b>  <i>Research aim: The aim of this study was to expose a group of well-trained cyclists to a high intensity training program to determine whether their heart rate recovery improved as they progressed through the training programme.</i>
<u>Study 3</u> (Chapter 4):	<b>Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters.</b>  <i>Research aim: The aim of this study was to retrospectively analyse the relationship between changes in heart rate recovery and cycling performance in a group of well-trained cyclists (n = 14) who participated in a 4 week high intensity training (HIT) program.</i>
<u>Study 4</u> (Chapter 5):	<b>Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status.</b>  <i>Research aim: The aim of this study was to determine the typical error of measurement of different laboratory tests for the prediction of performance, including the peak power output test and the 40km time trial, within a group of well-trained cyclists who maintained a constant training status.</i>
<u>Study 5</u> (Chapter 6):	<b>A novel submaximal test to predict and monitor cycling performance.</b>  <i>Research aim: The aim of this study was to determine the reliability and predictive value of parameters measured during a novel submaximal cycle protocol, on peak power and endurance cycling performance in well-trained cyclists.</i>
<u>Study 6</u> (Chapter 7):	<b>Measuring submaximal performance parameters to monitor fatigue and predict cycling performance: a case study of a world-class cyclo-cross cyclist.</b>  <i>Research aim: The aim of this study was to determine whether the LSCT is able to track changes in performance parameters, and objective and subjective markers of well-being such as resting heart rate, Daily Analysis of Life Demands for Athletes (DALDA) scores and Total Quality of Recovery (TQR) scores following changes in training load</i>

To meet the stylistic requirements of a thesis, the format of the published papers have been adjusted accordingly and abbreviations of units and terms standardised throughout. In addition, changes were made in Chapters 2 to 6 to accommodate the comments and suggestions of the examiners of the thesis. These edits did not change the content of the published papers in a substantial way.

Due to stylistic preferences of the different journals in which the studies were published, a faster or increased heart rate recovery (HRR) and a slower or decreased HRR are used interchangeably. A faster or increased HRR refers to a state in which heart rate recovers more beats in 60 seconds then before. A slower or decreased HRR refers to a state in which heart rate recovers less beats then before. The most commonly used abbreviations are mentioned in Table 1.2.

**Table 1.2** List of the most commonly used abbreviations.

Abbreviation	Meaning
40km TT	40km time trial
DALDA	Daily analysis of life demands for athletes
$G_{Decr}$	Subjects who showed a decrease in HRR during a HIT period
$G_{Incr}$	Subjects who showed a continuous increase in HRR during a HIT period
HIMS	Heart rate interval monitoring system
HIT	High intensity training
HR	Heart rate
HRR	Heart rate recovery
$HRR_{HIT}$	HRR after the HIT
$HRR_{40km}$	HRR after the 40km TT
$HRR_{60s}$	HRR over a 60 second period
$\%HR_{max}$	Percentage of heart rate maximum
HRV	Heart rate variability
LSCT	Lamberts and Lambert submaximal cycle test
PAR-Q	Physical activity readiness questionnaire
POMS	Profile of mood status
PPO	Peak power output test
RPE	Rate of perceived exertion
RPM	Revolutions per minute
TEM	Typical error of measurement
TQR	Total quality of recovery
$VO_{2max}$	Maximal oxygen uptake

Chapter 2 to 7 have all been peer reviewed and have either been published or accepted for publication. In Chapter 8 the outcomes of the 6 different studies are summarised, synthesised and interpreted as a whole. Additionally a hypothetical model describing how to interpret the different outcomes of the LSCT is presented in Chapter 8. Finally, recommendations are made for future research on how to improve the interpretation of the outcomes of LSCT.

## REFERENCES

- Arts FJ and Kuipers H (1994) The relation between power output, oxygen uptake and heart rate in male athletes. *Int J Sports Med* 15: 228-231
- Åstrand PO. *Experimental studies of physical working capacity in relation to sex and age*. (Dissertation). Ejnar Munksgaard, 1952.
- Åstrand PO and Ryhming I (1954) A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during sub-maximal work. *J Appl Physiol* 7: 218-221
- Bassett DR, Jr. and Howley ET (1997) Maximal oxygen uptake: "classical" versus "contemporary" viewpoints. *Med Sci Sports Exerc* 29: 591-603
- Bentley DJ, McNaughton LR, Thompson D, Vleck VE and Batterham AM (2001) Peak power output, the lactate threshold, and time trial performance in cyclists. *Med Sci Sports Exerc* 33: 2077-2081
- Borg GA (1970) Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med* 2: 92-98
- Borg GA (1982) Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 14: 377-381
- Borresen J and Lambert MI (2007) Changes in heart rate recovery in response to acute changes in training load. *Eur J Appl Physiol* 101: 503-511
- Borresen J and Lambert MI (2008) Autonomic control of heart rate during and after exercise - measurements and implications for monitoring training status. *Sports Med* 28: 633-646
- Brooks GD, Fahey TD and Baldwin KM (2005) Neural-endocrine Control of Metabolism: Blood Glucose Homeostasis During Exercise. (eds)

Exercise Physiology: Human Bioenergetics and Its Applications.  
McGraw-Hill, New York, NY, pp 181-211.

Bunc V, Heller J and Leso J (1988) Kinetics of heart rate responses to exercise. *J Sports Sci* 6: 39-48

Butland RJ, Pang J, Gross ER, Woodcock AA and Geddes DM (1982) Two-, six-, and 12-minute walking tests in respiratory disease. *Br Med J (Clin Res Ed)* 284: 1607-1608

Carter J and Jeukendrup AE (2002) Validity and reliability of three commercially available breath-by-breath respiratory systems. *Eur J Appl Physiol* 86: 435-441

Cole CR, Blackstone EH, Pashkow FJ, Snader CE and Lauer MS (1999) Heart-rate recovery immediately after exercise as a predictor of mortality. *N Engl J Med* 341: 1351-1357

Cooper KH (1968) A means of assessing maximal oxygen intake. Correlation between field and treadmill testing. *JAMA* 203: 201-204

Douglas CG (1911) A method for determining the total respiratory exchange in man. *J Physiol* 1-2

Duveen DI and Klickstein HS (1955) Antoine Laurent Lavoisier's contributions to medicine and public health. *Bull Hist Med* 29: 164-179

Ekblom B (2009) Counterpoint: maximal oxygen uptake is not limited by a central nervous system governor. *J Appl Physiol* 106: 339-341

Faria EW, Parker DL and Faria IE (2005) The science of cycling: physiology and training - part 1. *Sports Med* 35: 285-312



- Haber P, Schlick W, Schmid P and Mulac K (1976) Estimation of the performance spectrum of healthy adolescents by using the PWC 170 (Physical Work Capacity). *Acta Med Austriaca* 3: 164-166
- Halsen SL, Bridge MW, Meeusen R, Busschaert B, Gleeson M, Jones DA and Jeukendrup AE (2002) Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* 93: 947-956
- Halsen SL and Jeukendrup AE (2004) Does overtraining exist? An analysis of overreaching and overtraining research. *Sports Med* 34: 967-981
- Halsen SL, Lancaster GI, Jeukendrup AE and Gleeson M (2003) Immunological responses to overreaching in cyclists. *Med Sci Sports Exerc* 35: 854-861
- Hawley JA and Noakes TD (1992) Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur J Appl Physiol Occup Physiol* 65: 79-83
- Hill AV and Lupton H (1923) Muscular exercise, lactic acid, and the supply and utilization of oxygen. *Quarterly Journal of Medicine* 16: 135-171
- Hooper S, MacKinnon LT and Hanrahan S (1997) Mood states as an indication of staleness and recovery. *Int J Sport Psychol* 28: 1-12
- Jeukendrup A (2002) High-performance cycling. Human Kinetics Publishers, Inc., Champaign, IL, USA.
- Kenttä G and Hassmen P (1998) Overtraining and recovery. A conceptual model. *Sports Med* 26: 1-16
- Kline GM, Porcari JP, Hintermeister R, Freedson PS, Ward A, McCarron RF, Ross J and Rippe JM (1987) Estimation of  $\text{VO}_{2\text{max}}$  from a one-mile track walk, gender, age, and body weight. *Med Sci Sports Exerc* 19: 253-259

- Koutedakis Y and Sharp NC (1998) Seasonal variations of injury and overtraining in elite athletes. *Clin J Sport Med* 8: 18-21
- Laukkanen R, Oja P, Pasanen M and Vuori I (1992) Validity of a two kilometre walking test for estimating maximal aerobic power in overweight adults. *Int J Obes Relat Metab Disord* 16: 263-268
- Lehmann MJ, Lormes W, Opitz-Gress A, Steinacker JM, Netzer N, Foster C and Gastmann U (1997) Training and overtraining: an overview and experimental results in endurance sports. *J Sports Med Phys Fitness* 37: 7-17
- Levy WC, Cerqueira MD, Harp GD, Johannessen KA, Abrass IB, Schwartz RS and Stratton JR (1998) Effect of endurance exercise training on heart rate variability at rest in healthy young and older men. *Am J Cardiol* 82: 1236-1241
- Lucia A, Hoyos J, Perez M and Chicharro JL (2000) Heart rate and performance parameters in elite cyclists: a longitudinal study. *Med Sci Sports Exerc* 32: 1777-1782
- Lucia A, Hoyos J, Perez M, Santalla A and Chicharro JL (2002a) Inverse relationship between  $VO_{2max}$  and economy/efficiency in world-class cyclists. *Med Sci Sports Exerc* 34: 2079-2084
- Lucia A, Hoyos J, Santalla A, Perez M and Chicharro JL (2002b) Kinetics of  $VO_2$  in professional cyclists. *Med Sci Sports Exerc* 34: 320-325
- Martin DT, Andersen MB and Gates W (2000) Using Profile of Mood Status (POMS) to monitor high-intensity training in cyclists: Group versus case studies. *The Sport Psychologist* 138-156
- McNair DM, Lorr M and Droppleman LF (1971) Manual for the Profile of Mood Status. Educational and Industrial Testing Service, San Diego, CA.

- Meeusen R, Duclos M, Gleeson M, Rietjens GJ, Steinacker JM and Urhausen A (2006) Prevention, diagnosis and treatment of the overtraining syndrome. *Eur J Sport Sci* 6: 1-14
- Meeusen R, Piacentini MF, Busschaert B, Buyse L, De Schutter G and Stray-Gundersen J (2004) Hormonal responses in athletes: the use of a two bout exercise protocol to detect subtle differences in (over)training status. *Eur J Appl Physiol* 91: 140-146
- Meeusen R, Watson P, Hasegawa H, Roelands B and Piacentini MF (2007) Brain neurotransmitters in fatigue and overtraining. *Appl Physiol Nutr Metab* 32: 857-864
- Morgan WP, Brown DR, Raglin JS, O'Connor PJ and Ellickson KA (1987) Psychological monitoring of overtraining and staleness. *Br J Sports Med* 21: 107-114
- Nederhof E, Lemmink K, Zwerver J and Mulder T (2007) The effect of high load training on psychomotor speed. *Int J Sports Med* 28: 595-601
- Noakes TD (2008) Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *Br J Sports Med* 42: 551-555
- Noakes TD and Marino FE (2009) Point: maximal oxygen uptake is limited by a central nervous system governor. *J Appl Physiol* 106: 338-339
- Noakes TD, Peltonen JE and Rusko HK (2001) Evidence that a central governor regulates exercise performance during acute hypoxia and hyperoxia. *J Exp Biol* 204: 3225-3234
- O'Connor PJ, Morgan WP, Raglin JS, Barksdale CM and Kalin NH (1989) Mood state and salivary cortisol levels following overtraining in female swimmers. *Psychoneuroendocrinology* 14: 303-310

- Paton CD and Hopkins WG (2006) Ergometer error and biological variation in power output in a performance test with three cycle ergometers. *Int J Sports Med* 27: 444-447
- Raglin JS and Morgan WP (1994) Development of a scale for use in monitoring training-induced distress in athletes. *Int J Sports Med* 15: 84-88
- Rietjens GJ, Kuipers H, Adam JJ, Saris WH, van Breda E, van Hamont D and Keizer HA (2005) Physiological, biochemical and psychological markers of strenuous training-induced fatigue. *Int J Sports Med* 26: 16-26
- Robinson DM, Robinson SM, Hume PA and Hopkins WG (1991) Training intensity of elite male distance runners. *Med Sci Sports Exerc* 23: 1078-1082
- Robson P (2003) Elucidating the unexplained underperformance syndrome in endurance athletes : the interleukin-6 hypothesis. *Sports Med* 33: 771-781
- Roelands B, Hasegawa H, Watson P, Piacentini MF, Buyse L, De Schutter G and Meeusen RR (2008) The effects of acute dopamine reuptake inhibition on performance. *Med Sci Sports Exerc* 40: 879-885
- Rushall BS (1990) A Tool for Measuring Stress Tolerance in Elite Athletes. *Journal of Applied Sport Psychology* 2: 51-66
- Silva JM (2009) An analysis of training stress syndrome in competitive athletics. *Journal of Applied Sport Psychology* 5-20
- Singh SJ, Morgan MD, Scott S, Walters D and Hardman AE (1992) Development of a shuttle walking test of disability in patients with chronic airways obstruction. *Thorax* 47: 1019-1024
- Tenenbaum G, Jones CM, Kitsantas A, Sacks DN and Berwick JP (2003a) Failure adaptation: An investigation of the stress response process in sport. *International Journal of Sport Psychology* 27-62

- Tenenbaum G, Jones CM, Kitsantas A, Sacks DN and Berwick JP (2003b) Failure adaptation: Psychology conceptualization of the stress response process in sport. *International Journal of Sport Psychology* 1-26
- Trudeau F, Shephard RJ, Arsenault F and Laurencelle L (2003) Tracking of physical fitness from childhood to adulthood. *Can J Appl Physiol* 28: 257-271
- Tulppo MP, Makikallio TH, Seppanen T, Laukkanen RT and Huikuri HV (1998) Vagal modulation of heart rate during exercise: effects of age and physical fitness. *Am J Physiol* 274: H424-H429
- Urhausen A (2001) Overtraining: Making a difficult diagnosis and implimenting targeted treatment. *The Physician and Sportsmedicine* 29: 35-50
- Uusitalo ALT (2001) Making a difficult diagnosis and implementing treatment. *The Physician and Sportsmedicine* 5: 1-14
- Wagner PD (2000) New ideas on limitations to  $VO_{2max}$ . *Exerc Sport Sci Rev* 28: 10-14

# Chapter 2

**Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training \***

\* **R.P. Lamberts** and M.I. Lambert. Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. *Journal of Strength and Conditioning Research*, 23(3): 1005-1010, 2009

## ABSTRACT

**Introduction:** The HIMS test, which consists of controlled exercise at increasing workloads, has been developed to monitor changes in training status and accumulative fatigue in athletes. As the workload can influence the day-to-day variation in heart rate, the exercise intensity which is associated with the highest sensitivity needs to be established with the goal of refining the interpretability of these heart rate measurements. The aim of the study was to determine the within subject day-to-day variation of submaximal and recovery heart rate in subjects who reached different exercise intensities. **Methods:** Thirty-eight subjects participated in this study and after familiarization were allocated to one of four groups based on the percentage of predicted heart rate maximum which was elicited during the first test. (i.e. groups <85%, 85-90%, 90-95% and >95 % maximum heart rate). Variation in heart rate was determined for the following 4 days at a range of intensities (61–98% of maximum heart rate) and recovery periods. **Results:** Variation in heart rate decreased with increasing exercise intensity in all groups. The lowest variation in heart rate was found at the end of the last stage of the test in the 85-90% group ( $3 \pm 1$  beats·min<sup>-1</sup>) and >95% group ( $3 \pm 2$  beats·min<sup>-1</sup>). The lowest variation during the recovery periods occurred at the 1<sup>st</sup> minute after the last stage. Although there were no significant differences between the groups, the 85-90% group showed a tendency to have the lowest variation in heart rate. **Conclusion:** If changes in heart rate and heart rate recovery are to be monitored in athletes, a submaximal protocol should elicit heart rate in between 85-90% of maximum heart rate maximum, as this intensity is associated with the least day-to-day variation.

### Keywords:

Exercise intensity • Training status • Recovery • Precision • HIMS

## INTRODUCTION

An optimal approach to training requires finding the balance between an appropriate training stimulus followed by adequate recovery. If the balance in this relationship is not well controlled the athlete will either not improve or will eventually develop symptoms of fatigue including impaired performance (Kentta and Hassmén 1998; Meeusen *et al.* 2006).

In an attempt to accurately monitor training load and quantify recovery rate a variety of measurement tools have been developed (Lambert and Borresen 2006). An important feature of these measurement tools is that they should be easy to administer, non-invasive and sensitive to change. One such tool is the measurement of recovery heart rate (Hedelin *et al.* 2000; Jeukendrup and van Diemen 1998; Kuipers and Keizer 1988). For example, a recent study has shown that a 55% increase in training load over two weeks caused a slower heart rate recovery after submaximal exercise (Borresen and Lambert 2007). Other findings of this study showed that heart rate recovery tended to increase when training load was decreased.

To be able to use submaximal heart rate and heart rate recovery as a monitoring tool it is important to understand the precision of the measurement, in particular the intrinsic variation of heart rate. In accordance we conducted a study to determine day-to-day variation in submaximal and recovery heart rate in a group of active subjects who maintained a constant training load (Lamberts *et al.* 2004). This study showed that the within subject day-to-day variation in heart rate decreased as the intensity of the test increased, reaching the lowest variation at the highest exercise intensity ( $5 \pm 2 \text{ beats} \cdot \text{min}^{-1}$ ). The lowest variation in heart rate recovery occurred one minute after completing the test ( $8 \pm 3 \text{ beats} \cdot \text{min}^{-1}$ ).

A possible limitation of this study was that all subjects were exposed to the same absolute workload and because the subjects had varying physical activity habits, they reached different exercise intensities at the end of the test (78 to 100% of maximum heart rate). This may have implications for the interpretation of the test for two reasons; (i) day-to-day variation in heart rate decreases as exercise intensity



increases, and (ii) heart rate recovery may be affected as the starting point of recovery influences the rate of decline (Pierpont *et al.* 2000). From a practical perspective it would be prudent to design the test with the lowest possible variance in heart rate as this would improve the precision of the test, particularly when trying to detect small changes.

We hypothesized that the day-to-day variation in submaximal and recovery heart rate would be lower in subjects who reached a higher exercise intensity. In accordance the primary aim of this study was to determine the within subject day-to-day variation of submaximal and recovery heart rate within a group of subjects who reached different exercise intensities after undergoing a standardized exercise protocol. A secondary aim was to identify the exercise intensity that elicited the smallest day-to-day variation in both submaximal and recovery heart rate.

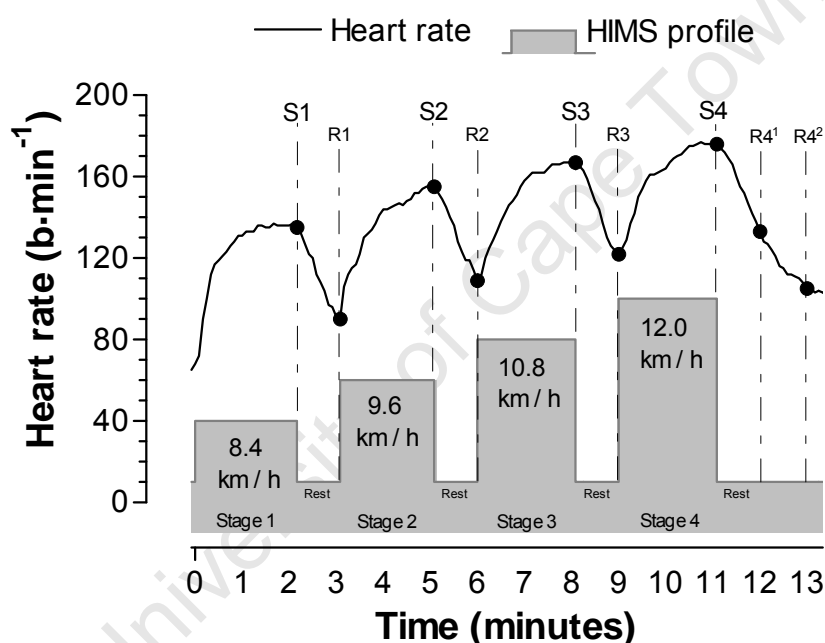
## METHODS

### ***Approach to the Problem***

Forty four subjects with different physical activity patterns but who were at least physically active twice a week and accustomed to running were recruited for the study. After the initial familiarization to the testing protocol, four different groups were identified based on submaximal heart rate reached at the end of the test. Day-to-day variation in heart rate over the following 4 consecutive day's, while undergoing the testing protocol, were recorded. All subjects were non-smokers and free of all cardiovascular risk factors (American College of Sports Medicine 1994). Before entering the testing period all subjects had to complete a medical screening questionnaire and signed informed consent after the study had been explained to them. The minimal sample size of each group was determined using the data of Lamberts *et al.* (2004). Assuming the smallest meaningful difference to be 9 beats·min<sup>-1</sup> (more than 8 beats·min<sup>-1</sup>) and a standard deviation of 4 beats·min<sup>-1</sup> (more than 3 beats·min<sup>-1</sup>) the sample size required for this study, in order to achieve a statistical power of 80% and a significance level of 5% was therefore n = 6 for each group (Altman 1991).

## Subjects

All subjects completed a submaximal interval based running test (Lamberts *et al.* 2004), also known as Heart rate Interval Monitoring System (HIMS) (Borresen and Lambert 2007), to familiarize themselves with the protocol, and then repeated the test on 4 consecutive days. All testing was done under controlled environment circumstances, scheduled for the same time of the day (Reilly *et al.* 1984) and only started after an informed consent form was signed. The study was approved by the Ethics and Research Committee of the Faculty of Health Sciences, University of Cape Town. The principles outlined by the Declaration of Helsinki and the ACSM guidelines for the Use of Humans were adopted in this study.



**Figure 2.1** An arbitrary heart rate response of one of the subjects during the Heart rate Interval Monitoring System (HIMS) test. A profile showing the increasing intensity and rest periods is also included on the Graphs. The dots (•) represent the different measuring points that were used to calculate the average heart rate of each stage.

## Procedures

The HIMS test is 13 minutes in duration and consists of 4 stages each being 2 minutes (Borresen and Lambert 2007). During the test subjects run back and forth between two lines drawn 20 meters apart on a rubberized floor in a sports hall. The pace of each of the 4 running stages (8.4 km·h<sup>-1</sup>, 9.6 km·h<sup>-1</sup>, 10.8 km·h<sup>-1</sup> and 12.0 km·h<sup>-1</sup> respectively) was controlled by a pre-recorded auditory signal. After each 2 minute stage the subjects rested and stood upright for 1 minute. During the HIMS,

and for two minutes after the end of the test heart rate was recorded with a Polar Accurex heart rate monitor (Polar Electro, Kempele, Finland). The heart rate for each *exercise intensity* (stage 1 (S1), stage 2 (S2), stage 3 (S3) and stage 4 (S4)) and each *recovery period* (recovery period 1 (R1), recovery period 2 (R2), recovery period 3 (R3) and recovery period 4 first and second minute (resp.  $R4^1$  and  $R4^2$ )) was calculated from the last final 15 seconds of each period. A schematic of this, including heart rate data from an arbitrary subject is shown in Figure 2.1.

### *General measurements*

On the first day of testing body mass, stature, body composition (Durnin and Womersley 1974) and the sum of seven skinfolds (triceps, biceps, subscapular, supra-iliac, abdominal, thigh, calf) (Ross and Marfell-Jones 1991) of each subject were determined. Body mass was measured before each test to control for any abnormal weight changes that may have affected heart rate (Durnin 1961; Edholm 1961; Khosla and Billewicz 1964; Robinson and Watson 1965). We decided to exclude subjects who had a body mass change of more than 1.5% during the study as this is considered to be more than the normal day-to-day variation in body mass (Khosla and Billewicz 1964; Robinson and Watson 1965).

To control for variation in submaximal heart rate subjects were asked to maintain their training and sleeping habits in the week before and during the week of testing. Subjects were also asked to refrain from ingesting excessive amounts of alcohol, wear the same shoes during all testing sessions and avoid caffeine two hours prior to testing. Subjects had to complete a questionnaire before each testing session to determine whether they had complied with all these requirements. Before each test subjects also had to rate their subjective assessment of general fatigue and muscle soreness on a scale from 0 (nothing at all) to 10 (maximal pain / fatigue).

### *Percent heart rate maximum and group allocation*

The percentage of predicted maximum heart rate (Keytel *et al.* 2005) which was elicited at the end of the test on day 1 was used to allocate subjects into one of four groups (<85%, 85-90%, 90-95% and >95% maximum heart rate).

### Statistical analysis

All data are expressed as means  $\pm$  standard deviation ( $X \pm s$ ). The coefficient of variation was calculated as (standard deviation/mean)  $\times$  100. The 95% confidence interval (CI) for the heart rate was determined for all stages and recovery periods. A one-way analysis of variance was used to determine differences in the general characteristics between groups. A two-way analysis of variance with repeated measures was used to determine if there were differences between groups across the different exercise intensities and recovery periods. Following the determination of a significant interaction (groups  $\times$  exercise intensity) a one-way ANOVA and LSD post-hoc test was used to identify these specific differences. Differences during the study for non-parametric variables (general fatigue and muscle fatigue scores) were determined using the Friedman's ANOVA. All data were analysed with STATISTICA version 7.0 (Stat-soft Inc., Tulsa, OK, USA) for any statistical significance ( $P < 0.05$ )

## RESULTS

Forty-four subjects were recruited for this study. After the analysis of changes in body mass during the study 6 subjects were excluded. The remaining subjects ( $n = 38$ ) had an average day-to-day variation in body mass of  $1.0 \pm 0.4\%$  over the 4 testing days. The general characteristics of the subjects in each group are shown in Table 2.1.

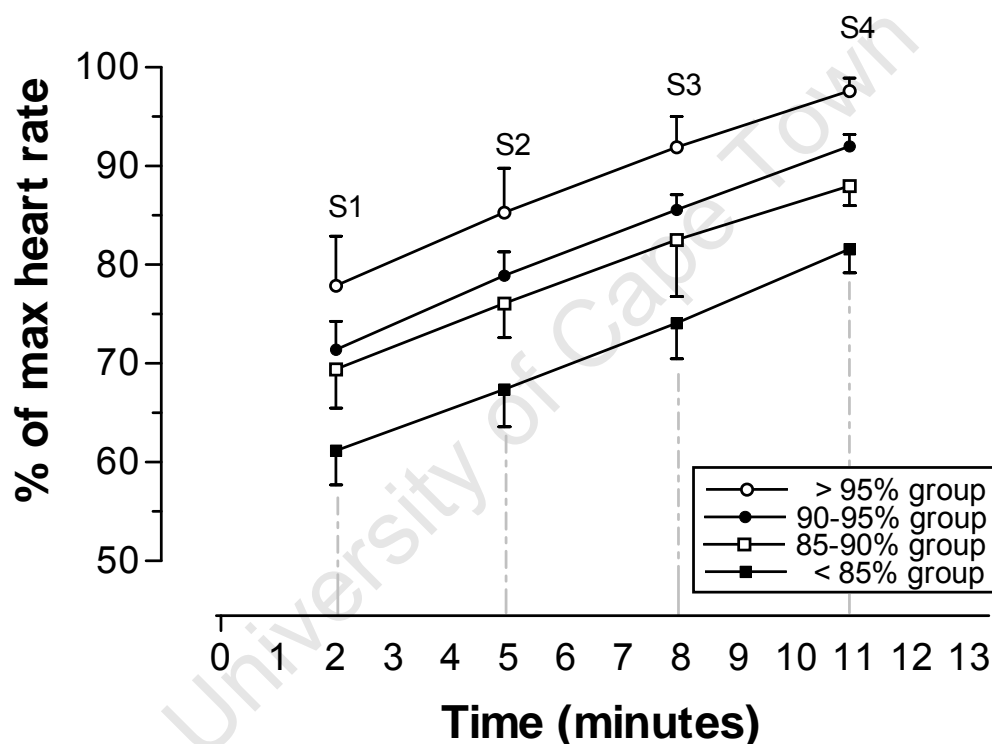
**Table 2.1** General descriptive characteristics of the subjects within each group ( $n=38$ ; ♂ = 21, ♀ = 17).

Variable	Groups			
(All values are expressed as $X \pm s$ )	< 85% n=6 (5♂,1♀)	85-90% n=9 (5♂,4♀)	90-95% n=10 (8♂,2♀)	> 95% n=13 (3♂,10♀)
Age (years)	29 $\pm$ 7	24 $\pm$ 4	26 $\pm$ 4	27 $\pm$ 7
Body mass (kg)	75.5 $\pm$ 5.0	70.9 $\pm$ 10.7	74.4 $\pm$ 9.6	61.7 $\pm$ 8.0 *
Stature (m)	1.78 $\pm$ 0.07	1.76 $\pm$ 0.09	1.76 $\pm$ 0.07	1.67 $\pm$ 0.05 *
Fat (%) ♂	14 $\pm$ 3	14 $\pm$ 2	13 $\pm$ 4	16 $\pm$ 5
Fat (%) ♀	23 $\pm$ 0	23 $\pm$ 3	27 $\pm$ 2	24 $\pm$ 3
Sum of 7 skinfolds (mm) ♂	58.7 $\pm$ 9.1	60.4 $\pm$ 12.1	56.9 $\pm$ 14.9	78.5 $\pm$ 35.5
Sum of 7 skinfolds (mm) ♀	84.7 $\pm$ 0.0	79.2 $\pm$ 16.9	97.7 $\pm$ 14.1	87.8 $\pm$ 22.4
Self reported physical activity (min $\cdot$ wk <sup>-1</sup> )	275 $\pm$ 48	263 $\pm$ 64	243 $\pm$ 99	191 $\pm$ 72

The subjects in group > 95% were slightly shorter and weighed less than the subjects in the other groups ( $p < 0.01$ ). The mean environmental conditions for these days were; temperature  $23 \pm 1$  °C; humidity  $55 \pm 1\%$ . All subjects were tested on 4 consecutive days and within a timeframe of  $33 \pm 19$  minutes.

### ***Variation in heart rate during exercise***

The percentage of maximum heart rate within each group during the four different stages of the HIMS test are shown in Figure 2.2.



**Figure 2.2** The percentage of heart rate maximum within each group during the 4 different stages of the HIMS test ( $\bar{X} \pm s$ ).

Day-to-day variation in heart rate for all stages of the HIMS are shown in Table 2.2. There was a significant interaction between the main effects of groups and the rate at which day-to-day variation in heart rate changed with increasing exercise intensity ( $P = 0.013$ ). The lowest day-to-day variation in heart rate for all groups occurred during stage 4 (S4) ( $P = 0.004$ ). Within stage 4 the smallest day-to-day variation was found in group 85-90% ( $3 \pm 1$  beats·min<sup>-1</sup>) and group >95% ( $3 \pm 2$  beats·min<sup>-1</sup>) ( $P < 0.031$ ).

**Table 2.2** Average, minimum and maximum range of the heart rate (beats·min<sup>-1</sup>), coefficient of variation and the 95% confidence interval of the different sub-maximal heart rate groups and for all subjects at the end of each stage (S1, S2, S3 and S4) of the HIMS.

Groups*	Average percentage of max. heart rate (%)	Average range of heart rate at the end of each stage (beats·min <sup>-1</sup> )	Minimum and maximum range for heart rate (beats·min <sup>-1</sup> )	Percentage change (%)	Coefficient of variation (%)	95% confidence interval for coefficient of variation
S1 < 85%	61.2 ± 3.5	6 ± 3	3 – 10	3.3 ± 1.3	2.5	1.4 – 3.0
85 – 90%	69.4 ± 3.9	8 ± 2	5 – 11	4.1 ± 1.0	2.6	2.1 – 1.5
90 – 95%	71.4 ± 2.9	8 ± 3	2 – 10	3.9 ± 1.3	2.5	1.9 – 3.0
> 95%	<b>77.9 ± 5.0</b>	<b>6 ± 3</b>	<b>2 – 10</b>	<b>3.1 ± 1.3</b>	<b>1.8</b>	<b>1.3 – 2.2</b>
S2 < 85%	67.4 ± 3.8	8 ± 2	6 – 11	4.2 ± 1.1	3.0	2.2 – 3.9
<b>85 – 90%</b>	<b>76.1 ± 3.5</b>	<b>6 ± 1</b>	<b>4 – 8</b>	<b>3.1 ± 0.6</b>	<b>1.9</b>	<b>1.6 – 2.3</b>
90 – 95%	78.9 ± 2.4	6 ± 2	4 – 10	3.3 ± 1.2	1.9	1.4 – 2.4
> 95%	85.3 ± 4.5	6 ± 3	3 – 12	3.1 ± 1.5	1.6	1.1 – 2.1
S3 < 85%	74.1 ± 3.6	6 ± 2	3 – 9	3.3 ± 1.3	2.0	1.0 – 3.0
<b>85 – 90%</b>	<b>82.5 ± 5.7</b>	<b>4 ± 1</b>	<b>3 – 6</b>	<b>2.2 ± 0.7</b>	<b>1.2</b>	<b>0.9 – 1.5</b>
90 – 95%	85.6 ± 1.5	6 ± 3	2 – 10	2.9 ± 1.4	1.5	1.0 – 2.1
> 95%	91.9 ± 3.1	5 ± 2	2 – 10	2.8 ± 1.3	1.3	1.0 – 1.7
S4 < 85%	81.6 ± 2.4	5 ± 3	2 – 9	2.7 ± 1.4	1.4	0.7 – 2.1
<b>85 – 90%</b>	<b>88.0 ± 2.0</b>	<b>3 ± 1<sup>#</sup></b>	<b>1 – 4</b>	<b>1.4 ± 0.6</b>	<b>1.0</b>	<b>0.7 – 1.4</b>
90 – 95%	92.0 ± 1.2	5 ± 2	1 – 8	2.4 ± 1.2	1.4	1.1 – 1.7
> 95%	97.6 ± 1.3	3 ± 2 <sup>#</sup>	1 – 6	1.4 ± 0.9	0.9	0.7 – 1.1

\*groups defined by percentage (%) heart rate maximum at the end of the 4<sup>th</sup> stage.

<sup>#</sup>  $P = 0.031$  S4 group 85-90% and group >95% vs. group <85% and group 90-95%

The group with the lowest variation is in **bold** for each stage

### Variation in heart rate during recovery

Day-to-day variation in heart rate during all recovery periods are shown in Table 2.3.

The day-to-day variation in recovery heart rate was the lowest in  $R4^1$  (i.e. the first minute of recovery after the last stage (S4)) compared with all other stages ( $P = 0.000001$ ). Although not significant, there was a tendency for the day-to-day variation in heart rate( $R4^1$ ) to be lower in group 85-90% compared with the other groups.

**Table 2.3:** Average, minimum and maximum range of the heart rate ( $\text{b}\cdot\text{min}^{-1}$ ), coefficient of variation and the 95% confidence interval of the different sub-maximal heart rate groups\* and for all subjects at the end of each recovery period (R1, R2 and R3) and one and two minutes after the fourth stage (R4<sup>1</sup> and R4<sup>2</sup>) of the HIMS.

	Groups*	Average percentage of max. heart rate (%)	Average range of heart rate at the end of each stage ( $\text{beats}\cdot\text{min}^{-1}$ )	Minimum and maximum range for heart rate ( $\text{beats}\cdot\text{min}^{-1}$ )	Percentage change (%)	Coefficient of variation (%)	95% confidence interval for coefficient of variation
R1	< 85%	33.4 ± 4.0	13 ± 6	5 - 20	6.6 ± 3.3	8.5	4.7 – 12.3
	<b>85 – 90%</b>	<b>41.6 ± 7.4</b>	<b>12 ± 4</b>	<b>4 - 16</b>	<b>6.3 ± 2.1</b>	<b>6.8</b>	<b>5.1 – 8.6</b>
	90 – 95%	44.9 ± 6.6	17 ± 8	3 - 31	8.7 ± 3.9	9.0	5.4 – 12.6
	> 95%	48.3 ± 9.1	13 ± 6	5 - 24	6.7 ± 2.9	6.2	4.4 – 7.9
R2	< 85%	38.1 ± 5.1	14 ± 7	6 - 23	6.6 ± 3.3	8.7	4.4 – 13.1
	85 – 90%	48.6 ± 7.8	11 ± 5	4 - 18	6.2 ± 2.7	5.8	3.8 – 7.9
	90 – 95%	52.6 ± 8.3	12 ± 5	3 - 21	6.1 ± 2.8	5.2	3.5 – 6.8
	<b>&gt; 95%</b>	<b>57.7 ± 9.7</b>	<b>12 ± 6</b>	<b>5 - 24</b>	<b>6.0 ± 3.2</b>	<b>4.9</b>	<b>3.4 – 6.4</b>
R3	< 85%	42.6 ± 5.5	14 ± 8	4 - 26	7.3 ± 4.6	8.1	1.7 – 14.6
	85 – 90%	55.7 ± 7.3	10 ± 3	7 - 16	5.2 ± 1.8	4.3	3.2 – 5.3
	<b>90 – 95%</b>	<b>59.9 ± 7.2</b>	<b>10 ± 6</b>	<b>4 - 25</b>	<b>5.0 ± 3.2</b>	<b>3.7</b>	<b>1.9 – 5.4</b>
	> 95%	66.0 ± 9.0	12 ± 7	3 - 23	6.4 ± 3.6	4.6	2.9 – 6.3
R4 <sup>1#</sup>	< 85%	53.3 ± 3.2	7 ± 3	4 - 11	3.6 ± 1.7	2.9	1.4 – 4.5
	<b>85 – 90%</b>	<b>63.1 ± 5.6</b>	<b>6 ± 2</b>	<b>3 - 9</b>	<b>2.2 ± 0.8</b>	<b>1.5</b>	<b>1.1 – 1.9</b>
	90 – 95%	67.6 ± 5.4	7 ± 4	4 - 15	3.6 ± 2.0	2.2	1.2 – 3.1
	> 95%	73.7 ± 7.1	8 ± 2	6 - 12	3.9 ± 1.3	2.4	1.9 – 2.9
R4 <sup>2</sup>	< 85%	42.1 ± 5.1	17 ± 7	6 - 22	3.6 ± 1.7	9.5	4.3 – 14.6
	<b>85 – 90%</b>	<b>50.5 ± 6.1</b>	<b>12 ± 6</b>	<b>8 - 26</b>	<b>4.3 ± 1.5</b>	<b>3.9</b>	<b>2.9 – 4.9</b>
	90 – 95%	54.4 ± 7.1	13 ± 8	5 - 26	5.1 ± 3.2	4.4	2.3 – 6.6
	> 95%	58.4 ± 8.4	15 ± 5	8 – 22	8.8 ± 4.2	4.9	3.5 – 6.3

\*groups defined by percentage (%) heart rate maximum at the end of the 4<sup>th</sup> stage.

#  $P = 0.000001$  R4<sup>1</sup> vs. R1, R2, R3 and R4<sup>2</sup>

The group with the lowest variation is in **bold** for each stage

### Other outcomes

There was a tendency for self reported physical activity to be lower in subjects who reached higher percentages of heart rate maximum ( $P = 0.08$ ) (Table 2.1). The general fatigue ( $2 \pm 2$  units) and muscle soreness ( $2 \pm 2$  units) scores remained similar throughout the study for all groups.

## DISCUSSION

The first finding of the study was that the day-to-day variation in heart rate decreased with increasing exercise intensity. This can be explained by different firing patterns of the autonomic nervous system which occurs as exercise intensity increases (Carter *et al.* 2003). The higher variations in heart rate at rest and lower exercise intensities can mainly be attributed to the dominant activity of the parasympathetic nervous system (Goldsmith *et al.* 2000). The parasympathetic drive withdraws as the exercise intensity increases up to about a 100 beats·min<sup>-1</sup> (Carter *et al.* 2003). This is followed by a combination of parasympathetic withdrawal and activation of the sympathetic nervous system (Goldsmith *et al.* 2000; Pierpont *et al.* 2000; Robinson *et al.* 1966) as the intensity increases further heart rate variation decreases as a result.

The second finding of the study was that the decrease in day-to-day variation was different between the four groups being lowest at the end of stage 4 (S4) in the 85-90% group ( $3 \pm 1$  beats·min<sup>-1</sup>) and > 95% group ( $3 \pm 2$  beats·min<sup>-1</sup>). This is in accordance with Lucia *et al.* (2000) who found a variation of 6 beats·min<sup>-1</sup> (95% Confidence interval) at a workload corresponding to 90% of maximum heart rate in 13 professional cyclists throughout a season which included a resting, pre-competition and in-competition testing phase. Other studies (Åstrand and Saltin 1961; Brisswalter and Legros 1994; Lucia *et al.* 2000) which examined day-to-day variation of heart rate at maximal exertion reported variations of 3 beats·min<sup>-1</sup> (95% Confidence interval) which is similar to what we found in the > 95% group.

The third finding of this study was that the day-to-day variation in heart rate was higher during the recovery periods when compared with the variation during exercise in the preceding work bout. During recovery after exercise the autonomic nervous system responds with a sympathetic withdrawal and parasympathetic reactivation (Kannankeril *et al.* 2004; Pierpont and Voth 2004; Shetler *et al.* 2001). As the parasympathetic drive will always be higher during a recovery period (Kannankeril *et al.* 2004) than during the preceding workload, it can be expected that the variation in heart rate during the recovery periods will also be higher.



The fourth major finding of this study was that the lowest day-to-day variation in heart rate during recovery occurred during the first minute after the highest exercise intensity and this variation was significantly lower than that found at the second minute after this exercise intensity. Although there were no differences between groups there was a tendency for the subjects who reached 85 - 90% of heart rate maximum in the last workload to have the lowest day-to-day variation ( $6 \pm 2$  beats·min<sup>-1</sup>). This variation was slightly higher in the group which reached heart rates > 95% of heart rate maximum ( $8 \pm 2$  beats·min<sup>-1</sup>). Lucia *et al.* (2000) reported variations in recovery heart rate of 7 beats·min<sup>-1</sup> (1 minute after the cessation of exercise) and 14 beats·min<sup>-1</sup> (2 minutes after the cessation of exercise) following a maximal cycle test. These findings are in accordance with the findings of our study, particularly within the > 95% group.

As changes in heart rates at fixed exercise intensities are associated with a state of overtraining, dehydration or a lack of conditioning (Hedelin *et al.* 2000; Jeukendrup and van Diemen 1998; Kuipers 1998; Montain and Coyle 1992), monitoring these changes can be of major importance for 'elite' athletes. However, before the changes in heart rate can be used in a prescriptive/diagnostic way the 'normal' day-to-day variation in heart rate needs to be established. This study contributes to a better understanding of the precision of monitoring heart rate during exercise and recovery as a marker of the state of training of a subject and shows that the precision is affected by the preceding workload and exercise intensity. Using the protocol designed for this purpose (HIMS) we found that the smallest day-to-day variation in heart rate was found at the end of stage 4 in the 85-90% and the >95% group. It is therefore logical to assume that these workloads represent the workloads that should be used in the testing protocol of a monitoring program that is designed to detect small changes in heart rate. As recovery of heart rate after exercise is faster in more physically active people (Bunc *et al.* 1988) and decreases after an acute increase in training load (Borresen and Lambert 2007), heart rate recovery has the potential to be a useful tool and sensitive marker of tracking changes in training status.

## **PRACTICAL APPLICATION**

Monitoring heart rate during and after submaximal exercise provides a practical and useful marker to monitor training status. For the highest precision, the chosen exercise intensity of a submaximal test should elicit a heart rate of in between 85-90% of heart rate maximum as the lowest day-to-day variation in submaximal heart rate and heart rate recovery were found at this intensity. From test-to-test a change in heart rate recovery of more then 6 beats·min<sup>-1</sup> and/or the change in submaximal heart rate of more then 3 beats·min<sup>-1</sup> can be regarded as a meaningful change under controlled conditions. These changes can be caused by an improved/decreased training status or the accumulation of fatigue as a result of functional overreaching (Hedelin *et al.* 2000; Meeusen *et al.* 2006).

## **ACKNOWLEDGEMENTS**

This study was funded by the van Ewijck foundation, Medical Research Council of South Africa, Discovery Health and the University of Cape Town Research Unit for Exercise Science and Sports Medicine research funds. Further Dr. Regan Arendse and Justin Durandt are thanked for their contribution in gathering the data.

## REFERENCES

- Altman DG (1991) Practical Statistics for Medical Research. Chapman and Hall, London, UK.
- American College of Sports Medicine (1994) Exercise for patients with coronary artery disease. Med Sci Sports Exerc 26: 1-5
- Åstrand PO and Saltin B (1961) Oxygen uptake during the first minutes of heavy muscular exercise. J Appl Physiol 16: 971-976
- Borresen J and Lambert MI (2007) Changes in heart rate recovery in response to acute changes in training load. Eur J Appl Physiol 101: 503-511
- Brisswalter J and Legros P (1994) Daily stability in energy cost of running, respiratory parameters and stride rate among well-trained middle distance runners. Int J Sports Med 15: 238-241
- Bunc V, Heller J and Leso J (1988) Kinetics of heart rate responses to exercise. J Sports Sci 6: 39-48
- Carter JB, Banister EW and Blaber AP (2003) Effect of endurance exercise on autonomic control of heart rate. Sports Med 33: 33-46
- Durnin JVGA (1961) Basic physiological factors affecting calorie balance. Proc Nutr Soc 20: 52-58
- Durnin JVGA and Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br J Nutr 32: 77-97
- Edholm OG (1961) Energy expenditure and calorie intake in young men. Proc Nutr Soc 20: 71-76
- Goldsmith RL, Bloomfield DM and Rosenwinkel ET (2000) Exercise and autonomic function. Coron Artery Dis 11: 129-135

- Hedelin R, Kenttä G, Wiklund U, Bjerle P and Henriksson-Larsen K (2000) Short-term overtraining: effects on performance, circulatory responses, and heart rate variability. *Med Sci Sports Exerc* 32: 1480-1484
- Jeukendrup AE and van Diemen A (1998) Heart rate monitoring during training and competition in cyclists. *J Sports Sci* 16: S91-S99
- Kannankeril PJ, Le FK, Kadish AH and Goldberger JJ (2004) Parasympathetic effects on heart rate recovery after exercise. *J Investig Med* 52: 394-401
- Kentta G and Hassmén P (1998) Overtraining and recovery. A conceptual model. *Sports Med* 26: 1-16
- Keytel LR, Goedecke JH, Noakes TD, Hiiloskorpi H, Laukkanen R, van der ML and Lambert EV (2005) Prediction of energy expenditure from heart rate monitoring during submaximal exercise. *J Sports Sci* 23: 289-297
- Khosla LA T and Billewicz WZ (1964) Measurement of change in body-weight. *Br J Nutr* 18: 227-239
- Kuipers H (1998) Training and overtraining: an introduction. *Med Sci Sports Exerc* 30: 1137-1139
- Kuipers H and Keizer HA (1988) Overtraining in elite athletes. Review and directions for the future. *Sports Med* 6: 79-92
- Lambert MI and Borresen J (2006) A theoretical basis of monitoring fatigue: a practical approach for coaches. *International Journal of Sports Science & Coaching* 1: 371-388
- Lamberts RP, Lemmink KA, Durandt JJ and Lambert MI (2004) Variation in heart rate during submaximal exercise: implications for monitoring training. *J Strength Cond Res* 18: 641-645
- Lucia A, Hoyos J, Perez M and Chicharro JL (2000) Heart rate and performance parameters in elite cyclists: a longitudinal study. *Med Sci Sports Exerc* 32: 1777-1782

- Meeusen R, Duclos M, Gleeson M, Rietjens G, Steinacker J and Urhausen A (2006) Prevention, diagnosis and treatment of the overtraining syndrome. *European Journal of Sports Science* 6: 1-14
- Montain SJ and Coyle EF (1992) Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *J Appl Physiol* 73: 1340-1350
- Pierpont GL, Stolpmann DR and Gornick CC (2000) Heart rate recovery post-exercise as an index of parasympathetic activity. *J Auton Nerv Syst* 80: 169-174
- Pierpont GL and Voth EJ (2004) Assessing autonomic function by analysis of heart rate recovery from exercise in healthy subjects. *Am J Cardiol* 94: 64-68
- Reilly T, Robinson G and Minors DS (1984) Some circulatory responses to exercise at different times of day. *Med Sci Sports Exerc* 16: 477-482
- Robinson BF, Epstein SE, Beiser GD and Braunwald E (1966) Control of heart rate by the autonomic nervous system. Studies in man on the interrelation between baroreceptor mechanisms and exercise. *Circ Res* 19: 400-411
- Robinson MF and Watson PE (1965) Day-to-day variations in body-weight of young women. *Br J Nutr* 19: 225-235
- Ross WD and Marfell-Jones MJ (1991) Kinanthropometry. In: MacDougall JD, Wenger HA and Green HS. (eds) *Physiological Testing of the High Performance Athlete*. Champaign, IL: Human Kinetics, pp 223-308.
- Shetler K, Marcus R, Froelicher VF, Vora S, Kalisetti D, Prakash M, Myers J and Do D (2001) Heart rate recovery: Validation and methodologic issues. *J Am Coll Cardiol* 38: 1980-1987

# Chapter 3

## Changes in heart rate recovery after high intensity training in well-trained cyclists \*

\* **R.P. Lamberts**, J. Swart, T.D. Noakes and M.I. Lambert. *Changes in heart rate recovery after high intensity training in well-trained cyclists. European Journal of Applied Physiology*, 5: 705-713, 2009

**ABSTRACT**

Heart rate recovery (HRR) after submaximal exercise improves after training. However, it is unknown if this also occurs in already well-trained cyclists. Therefore, 14 well-trained cyclists ( $\text{VO}_{2\text{max}}$   $60.3 \pm 7.2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ; relative peak power output  $5.2 \pm 0.6 \text{ W}\cdot\text{kg}^{-1}$ ) participated in a high-intensity training programme (8 sessions in 4 weeks). Before and after high intensity training performance was assessed with a peak power output test including respiratory gas analysis ( $\text{VO}_{2\text{max}}$ ) and a 40km time trial. HRR was measured after every high intensity training session and 40km time trial. After the training period peak power output, expressed as  $\text{W}\cdot\text{kg}^{-1}$ , improved by 4.7% ( $P = 0.000010$ ) and 40km time trial improved by 2.2% ( $P = 0.000007$ ) whereas there was no change in  $\text{VO}_{2\text{max}}$  ( $P = 0.066571$ ). Both HRR after the high intensity training sessions ( $7 \pm 6$  beats;  $P = 0.001302$ ) and HRR after the 40km time trials ( $6 \pm 3$  beats;  $P = 0.023101$ ) improved significantly after the training period. Good relationships were found between improvements in  $\text{HRR}_{40\text{km}}$  and improvements in peak power output ( $r = 0.73$ ;  $P < 0.0001$ ) and 40km time trial time ( $r = 0.96$ ;  $P < 0.0001$ ). In conclusion, HRR is a sensitive marker which tracks changes in training status in already well-trained cyclists and has the potential to have an important role in monitoring and prescribing training.

**Keywords:**

Cycling; Monitoring · Performance · Adaptation · Autonomic nervous system

## INTRODUCTION

To achieve a high level of performance, competitive cyclists must strive to find a balance between the most appropriate training load followed by a minimal, though adequate recovery period. While training load can be influenced by intensity, volume, frequency and duration, recovery is influenced by less controllable factors such as stress, sleeping patterns, nutrition and psychological and sociological wellbeing (Jeukendrup 2002; Kenttä and Hassmén 1998). If the training load is too high and/or the recovery period is insufficient, the applied training load cannot be tolerated and symptoms of fatigue will develop. A continuous imbalance in this relationship will lead to 'functional' or 'non-functional' overreaching and can in the long term develop into an overtraining syndrome with detrimental effects on performance (Meeusen *et al.* 2006).

A variety of measurement tools have been developed in an attempt to predict and monitor changes in training status (Lambert and Borresen 2006). Most of these methods aim, either directly or indirectly, to measure the overall wellbeing of the athlete in response to the applied training load. However, no single measurement has yet been identified that predicts with consistent precision the imminent symptoms of fatigue (Lambert and Borresen 2006). This limits the practical application of these measurements. A more objective way of quantifying 'coping with training load' might be to analyse the response of the autonomic nervous system to training. The autonomic nervous system consists of parasympathetic and sympathetic components and is interlinked with many other physiological systems (Borresen and Lambert 2008; Kiviniemi *et al.* 2007). The responsiveness of the autonomic nervous system may therefore provide useful information about the functional adaptations of the human body. It is known that sympathetic hyperactivity or reduced parasympathetic activity is associated with an increased risk of cardiac disease and overall mortality (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996). Similarly studies have found altered autonomic nervous system function in overtrained athletes (Kuipers 1998; Lehmann *et al.* 1998; Lehmann *et al.* 1997).



Two non-invasive methods that measure autonomic nervous system functioning and modulation are the measurement of heart rate variability (HRV) (Baumert *et al.* 2006; Kiviniemi *et al.* 2007; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996) and heart rate recovery (HRR) after exercise (Borresen and Lambert 2007; Hedelin *et al.* 2000; Lamberts *et al.* 2004). HRR is determined as the rate at which heart rate decreases after cessation of moderate to heavy exercise (Shetler *et al.* 2001). One of the first papers which specifically studied HRR after exhausting exercise was published in 1931 (Boas 1931). Since then it has become general knowledge that HRR recovers faster in well-trained compared to untrained subjects after similar intensities (Bunc *et al.* 1988; Short and Sedlock 1997) and recently that a low HRR is associated with a higher risk on overall mortality (Cole *et al.* 1999). However, only a few studies have investigated the longitudinal effects of training on HRR in healthy subjects (Borresen and Lambert 2007; Sugawara *et al.* 2001; Yamamoto *et al.* 2001).

HRR improved in a study of previously untrained men who were exposed to 8 weeks of endurance cycle training and then reverted back to the pre-training levels following the 4 weeks of detraining (Sugawara *et al.* 2001). Another study showed that resting heart rate decreased and HRR improved after 6 weeks of endurance training (Yamamoto *et al.* 2001). The authors concluded the training induced changes associated with the autonomic control with heart rate occurred sooner in the recovery period after exercise than at rest. This suggests that HRR has the potential to be a sensitive tool that tracks changes in performance parameters.

Buchheit *et al.* (2008) showed an improved HRR and HRV indices in physically active subjects after 9 weeks of high intensity training and concluded that HRR indices are more sensitive training markers than HRV indices (Buchheit *et al.* 2007; Buchheit *et al.* 2008). However, it is not known whether the same changes in HRR also occur in already well-trained subjects with improvements in performance.

Accordingly, the aim of this study was to expose a group of well-trained cyclists to a high intensity training program to determine whether their HRR improved as they progressed through the training programme. We hypothesised that HRR would track changes in performance in these cyclists.

## METHODS

### ***Recruitment***

The sample size for this study was determined using the data of Lamberts *et al.* (2004), which showed that the day-to-day variability of sub-maximal heart rate and HRR, 60 seconds after exercise was about 5-6 and 7-8  $\text{b}\cdot\text{min}^{-1}$  respectively (these values were defined as the 95% confidence intervals of within subject range), with a standard deviation of 3  $\text{b}\cdot\text{min}^{-1}$ . As this study was conducted on physically active subjects who maintained their training load, the smallest meaningful difference in the current study was defined as 9  $\text{b}\cdot\text{min}^{-1}$  with a standard deviation of 6  $\text{b}\cdot\text{min}^{-1}$  to accommodate possible effects of variations in response to the training. Using these parameters the sample size was calculated to be  $n = 7$  (to achieve a statistical power of 80% and a significance level of 5%) (Altman 1991). However, due to the nature of the training study (high intensity) and the expected high drop out rate, we decided to recruit more subjects to assure sufficient statistical power.

Sixteen well-trained male cyclists, with at least 3 years of cycling experience and a minimal training load of 6 hours per week, were recruited to participate in this study. After being fully informed about the risks and stresses associated with the research protocol, all subjects completed a Physical Activity Readiness Questionnaire (PAR-Q) (American College of Sports Medicine 2007), were personally interviewed about their training history and their training logs were analysed. The study was approved by the Ethics and Research Committee of the Faculty of Health Sciences of the University of Cape Town and all subjects signed an informed consent before entering the study.

### ***Study design***

Prior to the testing and training period all cyclists performed a 40km familiarization time trial on an electronically braked cycle ergometer (Computrainer<sup>TM</sup> Pro 3D, RacerMate, Seattle, USA) over a flat course.

Three days before the start of the training period a peak power output test (PPO) was performed, which included respiratory gas analysis for measurement of maximal oxygen consumption ( $\text{VO}_{2\text{max}}$ ), followed by a 40km time trial (40km TT) 48 hours after

the PPO test and one day before the start of the training period. After completing the initial tests, subjects started their training protocol which consisted of two high intensity training (HIT) sessions, two ninety minute recovery rides below lactate threshold (Solberg *et al.* 2005) and three resting days each week, for 4 weeks. During all testing and training subjects were blinded to any feed-back of time, power output, heart rate and speed to prevent them adopting a pacing strategy with the potential of biasing the performance outcomes. The only exception to this was the display of completed distance during the 40km TT. Additionally subjects were asked to avoid participating in any racing or prolonged or high intensity exercise during the study. Each subject was asked to maintain a detailed training diary and to record all heart rate data during all training sessions performed outside of the laboratory for the duration of the study. Subjects were questioned and training logbooks inspected prior to the second testing phase to ensure that they had adhered to the training protocol.

#### ***Warming-up and calibration.***

Before all testing and training sessions subjects performed a self-paced 15 minute warm-up ride on a simulated 40km flat TT course. Testing and training was done on the subject's own bicycle which was mounted on to the Computrainer<sup>TM</sup> ergometer system. The rear wheel was inflated to 800 kPa after which the system's load generator was calibrated to a rolling resistance of between 0.88-0.93 kg. This calibration procedure was done before and directly after the 15 minute warming up period to ensure accurate calibration as recommended by Davidson *et al.* (Davison *et al.* 2007). The mean overall rolling resistance of the Computrainer<sup>TM</sup> system during all testing and training sessions was calibrated to  $0.9110 \pm 0.0186$  kg.

All test and training sessions were done under stable climate conditions ( $22.3 \pm 1.3$  °C,  $53.7 \pm 2.4\%$  relative humidity,  $101.9 \pm 0.8$  kPa) and at a similar time of day (within 60 min). Body mass was measured continuously throughout the study whenever a subject visited the laboratory for either a testing or training session. Body fat percentage (Durnin and Womersley 1974) was calculated from the sum of seven skinfolds (triceps, biceps, supra-iliac, sub-scapular, calf, thigh and abdomen) measured with the methods described by Ross and Marfell Jones (1991) before the start of both 40km TT's. Stature was measured before the first 40km TT.

### **Performance tests**

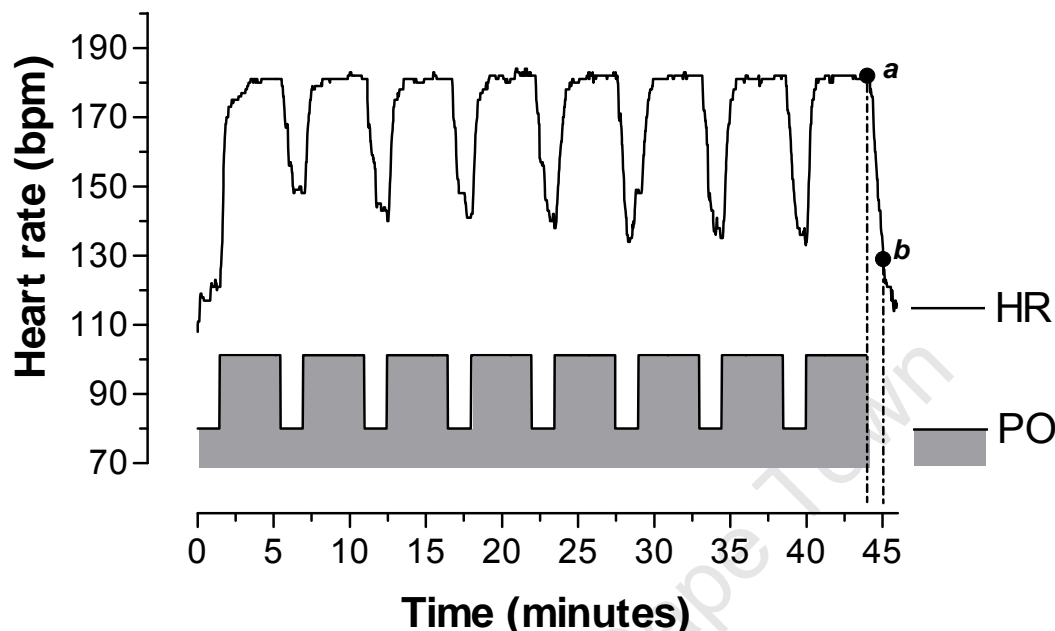
Outcomes of the 40km TT and the peak power output (PPO) test, which included respiratory gas analysis ( $\text{VO}_{2\text{max}}$ ), were used as markers of cycling performance (Hawley and Noakes 1992; Lucia *et al.* 2002b; Lucia *et al.* 2002a; Mujika and Padilla 2001; Padilla *et al.* 2000). These tests were conducted before training and again after the 28 day training period which was followed by a 10 day low intensity recovery period. This tapering period allowed the cyclists to recover from their HIT session before they were re-tested (Jeukendrup 2002; Shepley *et al.* 1992).

All subjects were asked to perform a 90 minute submaximal recovery ride 24 hours prior to the different tests. The PPO test was performed at a starting work rate of  $2.50 \text{ W}\cdot\text{kg}^{-1}$  body mass after which the load was increased incrementally by 20 W each minute until the cyclist could not sustain a cadence greater than 70 rpm or was volitionally exhausted. During this test ventilation volume ( $V_E$ ), oxygen uptake ( $\text{VO}_2$ ) and  $\text{CO}_2$  production ( $\text{VCO}_2$ ) were measured over 15 second intervals using an on-line breath-by-breath gas analyser and pneumotach (Oxycon, Viasis, Hoechberg, Germany). Subjects were verbally encouraged to perform to maximal exhaustion. Maximal peak power output was determined as the mean power output during the final minute of the PPO test whereas  $\text{VO}_{2\text{max}}$  ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) was defined as the highest recorded reading over a 30 second period. The PPO test was accepted as being maximal if the subjects had a minimal respiratory exchange ratio of 1.15 and a slow decrease in cadence despite attempting to maintain their power output as they approached the end of the test. The 40km TT was performed on a simulated 40km flat time trial course which was programmed into the Computrainer<sup>TM</sup>. Subjects were allowed to drink water *ad libitum* throughout the test and were given clear instructions to complete the 40km distance in the fastest possible time. All subjects refrained from any food in the last 2 hours and from any caffeine in the last 3 hours before all performance testing and training sessions.

### **Training sessions**

All subjects followed the same structured training program which included HIT training sessions, rest days and recovery rides. One HIT training session consisted of 8 intervals at approximately 80% of peak power output, determined for each subject during the initial PPO test. Each interval of 4 minute was followed by a 90 second self

paced recovery (Figure 3.1). All HIT sessions were closely supervised while speed ( $\text{km}\cdot\text{h}^{-1}$ ), power output (W), cadence (rpm)) and heart rate ( $\text{beats}\cdot\text{min}^{-1}$ ) were captured at a rate of 34 Hz.



**Figure 3.1** The average heart rate (HR) response of an arbitrary subject undergoing a high intensity training session (see power profile (PO) below). **a.** represents the start of the heart rate recovery measurement ( $\text{HRR}_{\text{HIT}}$ ). **b.** represents the end of the heart rate recovery measurement ( $\text{HRR}_{\text{HIT}}$ ).

### **Heart rate and heart rate recovery**

During all performance tests and training sessions heart rate was recorded continuously at a capturing rate of 34 Hz by the Computrainer™ software. HRR after the HIT sessions ( $\text{HRR}_{\text{HIT}}$ ) was also recorded with the Computrainer™ software where as the HRR after the 40km time trials ( $\text{HRR}_{40\text{km}}$ ) was recorded with a heart rate monitor at 5 second intervals (Polar Sport Tester, Polar Electro, Kempele, Finland).

HRR was calculated as described previously (Borresen and Lambert 2007; Lamberts *et al.* 2004) and defined as the reduction in heart rate within the first 60 seconds after the cessation of the 8<sup>th</sup> interval of an HIT session ( $\text{HRR}_{\text{HIT}}$ ) or the 40km TT ( $\text{HRR}_{40\text{km}}$ ). In an attempt to control factors which could influence heart rate and HRR, subjects were asked to sit passively straight up on their cycles (Gnehm *et al.* 1997), remain still and were not allowed to talk during the recovery period.

## Data analysis

Analysis of performance and training data were performed using CyclingPeaks™ analysis software (WKO+ edition, Version 2.1, 2006, Lafayette, CO, USA) and the Computrainer™ coaching software (Version 1.5.308, RacerMate, Seattle, USA). Data were expressed as absolute values where changes in performance parameters were expressed in absolute and relative (percentages) values. Percentage change was calculated as;

$$\text{Percentage change} = \frac{(\text{Post training session value} - \text{pre training session value})}{(\text{Pre training session value})} \times 100$$

To compare the changes in  $\text{VO}_{2\text{max}}$  and PPO both these measurements were calculated and expressed per kg ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  and  $\text{W}\cdot\text{kg}^{-1}$ , respectively). Heart rate data were analysed with CyclingPeaks™ analysis software and Polar precision performance software (Version 4.03.049, Polar Electro, Kempele, Finland).

## Statistical Analysis

The data were analysed with STATISTICA version 7.0 (Stat-soft Inc., Tulsa, OK, USA) for any statistical significance ( $P < 0.05$ ). All data are expressed as means  $\pm$  standard deviations. A T-test with dependent variables was used to determine any training-induced changes in performance parameters (PPO,  $\text{VO}_{2\text{max}}$ , 40km TT and  $\text{HRR}_{40\text{km}}$ ). A one-way analysis of variance with repeated measures was used to determine any differences in the HRR measured during the HIT sessions ( $\text{HRR}_{\text{HIT}}$ ). Sphericity of the data was tested using the Mauchley test. When the sphericity condition was violated a Greenhouse-Geisser adjustment was made to the degrees of freedom to counter the increased risk of a type 1 error. Relationships between changes in performance parameters and changes in  $\text{HRR}_{40\text{km}}$  were established using a Pearsons Product moment correlation (GraphPad Prism version 3.00 for Windows, GraphPad Software, San Diego, California, USA). Confidence intervals of the correlations were calculated using a spreadsheet designed for this purpose and downloaded from [www.sportsci.org](http://www.sportsci.org).

## RESULTS

Two subjects were unable to complete the study as the result of a fractured wrist and a viral illness respectively and their data were excluded from further analysis. The general characteristics of the remaining 14 cyclists are shown in Table 3.1. Based on the mean peak power output, power to weight ratios, average amount of training hours per week and years of competitive cycling, all cyclists could be regarded as well-trained (Jeukendrup 2002; Jeukendrup *et al.* 2000). The average training load over the last 6 weeks before the start of the HIT training period was  $11 \pm 4$  hours per week which was mainly out of base training.

**Table 3.1** General descriptive characteristics of the fourteen cyclists, expressed as  $X \pm s$ .

Variable	
Age (years)	$30 \pm 6$
Stature (cm)	$179 \pm 7$
Body mass (kg)	$73.3 \pm 8.0$
Fat (%)	$14.2 \pm 3.6$
Sum of skinfolds (mm)	$57.8 \pm 18.8$
Peak power output (W)	$376 \pm 32$
Power to weight ratio ( $W \cdot kg^{-1}$ )	$5.2 \pm 0.6$
$VO_{2max}$ ( $ml \cdot kg^{-1} \cdot min^{-1}$ )	$60.3 \pm 7.2$
Average 40 km TT time (min.s)	$65.26 \pm 2.25$
Years of competitive cycling (years)	$10.2 \pm 6.4$
Training hours per week (hours)	$11 \pm 4$

### Performance

All performance parameters except for  $VO_{2max}$  improved after the HIT period (Table 3.2). Mean peak power output expressed as  $W \cdot kg^{-1}$  improved by  $4.7 \pm 3.1\%$ , while  $VO_{2max}$  ( $ml \cdot kg^{-1} \cdot min^{-1}$ ) only showed a tendency for improvement ( $P = 0.066$ ). Both PPO tests, which were done before and after the training period, produced similar maximal heart rates ( $189 \pm 9$  vs.  $189 \pm 10$   $b \cdot min^{-1}$ ) with a maximal difference of 3 beats. The respiratory exchange ratio's to of  $1.24 \pm 0.04$  and  $1.25 \pm 0.04$  (respectively) assured that both test were performed at maximal effort. Mean time for the 40km TT improved by  $2.2 \pm 1.2\%$ .

**Table 3.2** Performance parameters before and after the training period, expressed as  $X \pm s$ .

Variable	Before	After	P-value
Peak power output (W)	376 $\pm$ 32	389 $\pm$ 34	0.000613
Relative peak power (W·kg <sup>-1</sup> )	5.2 $\pm$ 0.6	5.4 $\pm$ 0.5	0.000010
VO <sub>2max</sub> (ml·kg <sup>-1</sup> ·min <sup>-1</sup> )	60.3 $\pm$ 7.2	61.7 $\pm$ 6.5	0.066571
40km TT time (min.s)	65.26 $\pm$ 2.25	63.56 $\pm$ 2.00	0.000016
Mean power during the 40km TT (W)	255 $\pm$ 26	270 $\pm$ 24	0.000007
Relative power during the 40km TT (W·kg <sup>-1</sup> )	3.5 $\pm$ 0.5	3.7 $\pm$ 0.4	0.000043

### Heart rate recovery after the 40km TT (HRR<sub>40km</sub>)

HRR<sub>40km</sub> improved by 6  $\pm$  3 beats ( $P = 0.023101$ ) after completing the HIT period. The average HRR<sub>40km</sub> improved from 29  $\pm$  6 beats before to 35  $\pm$  4 beats after the training period which is equivalent to a 21  $\pm$  16% improvement ( $P = 0.000023$ ). The intensity (% HR<sub>max</sub>) and heart rate from which HRR<sub>40km</sub> was measured was similar before and after the training period (97  $\pm$  1% (183  $\pm$  10 b·min<sup>-1</sup>) vs. 98  $\pm$  2% (184  $\pm$  9 b·min<sup>-1</sup>) respectively).

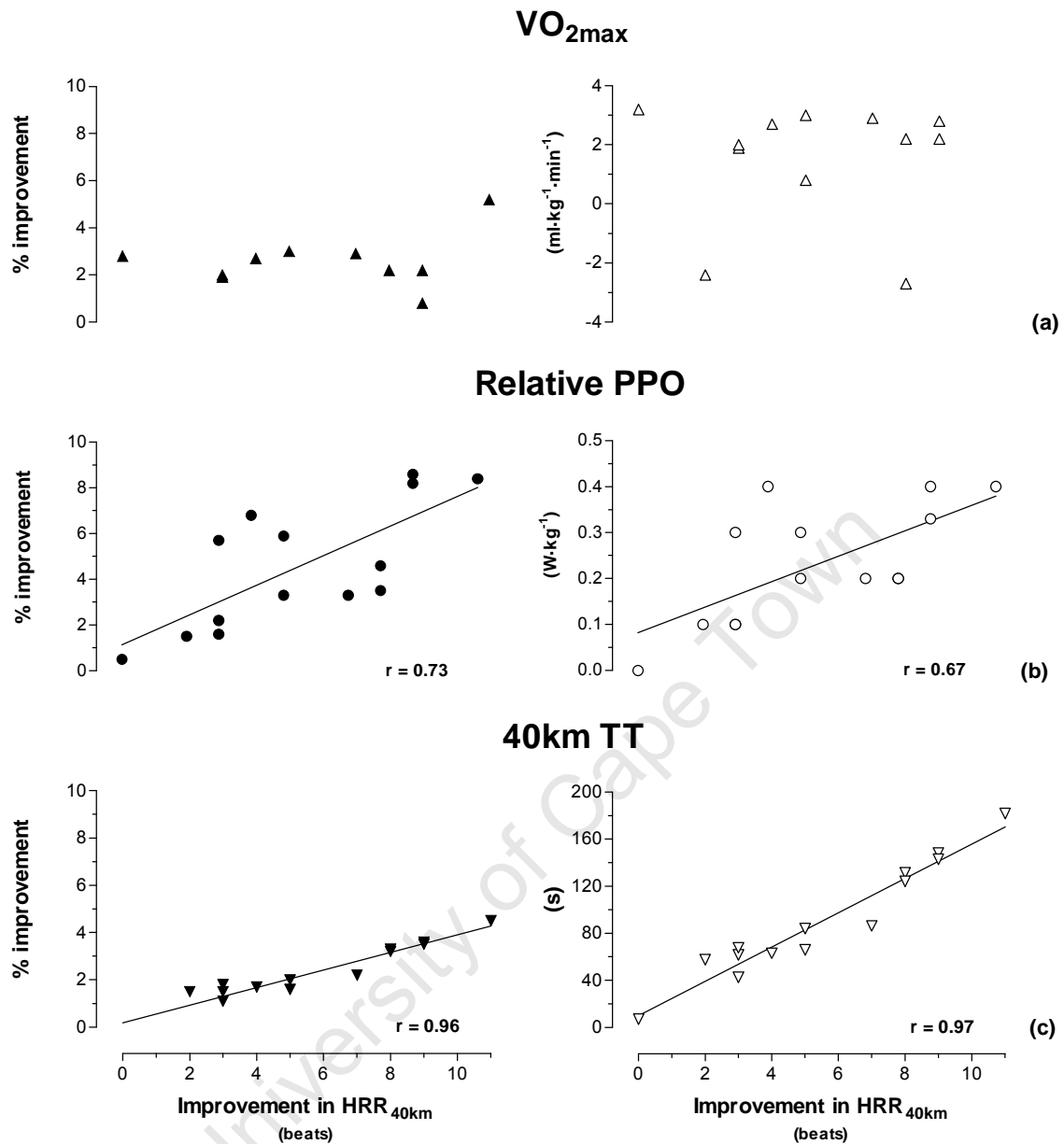
### Relationships between HRR<sub>40km</sub> and change in performance parameters

When analyzing the improvements in HRR<sub>40km</sub> and the improvements in performance parameters two strong relationships were found (Figure 3.2). Improvement in 40km TT time, both absolute and when expressed as a percentage, correlated very well with improvements in HRR<sub>40km</sub>,  $r = 0.97$ ; 95% CI: 0.91-0.99 ( $P < 0.0001$ ) and  $r = 0.96$ ; 95% CI: 0.88-0.99 ( $P < 0.0001$ ) respectively. A similar relationship, but slightly weaker, was found between HRR<sub>40km</sub> and improvement in absolute and relative peak power output and when expressed as percentage improvement, ( $r = 0.67$ ; 95% CI 0.22-0.89 ( $P < 0.0081$ ) and ( $r = 0.73$ ; 95% CI 0.33-0.91 ( $P < 0.0027$ ) respectively).

### Heart rate recovery during high intensity training (HRR<sub>HIT</sub>)

The intensity (% HR<sub>max</sub>) at the end of each HIT sessions remained constant throughout the eight HIT sessions (93  $\pm$  2% (175  $\pm$  2 b·min<sup>-1</sup>)). HRR<sub>HIT</sub> improved throughout the entire training period, being significantly higher at the 5<sup>th</sup>, 6<sup>th</sup>, 7<sup>th</sup> and 8<sup>th</sup> HIT session compared to the 1<sup>st</sup> HIT session (Table 3.3).





**Figure 3.2** Improvement in HRR<sub>40km</sub> vs. absolute (open symbols) and relative (closed symbols) improvements in (a) VO<sub>2max</sub>, (b) relative PPO and (c) 40km TT time.

HRR<sub>HIT</sub> improved by  $7 \pm 6$  beats ( $P = 0.001302$ ) beats per minute between the 8<sup>th</sup> and 1<sup>st</sup> HIT session. The largest change with the lowest standard deviation was found between the 6<sup>th</sup> and the 1<sup>st</sup> HIT session,  $7 \pm 4$  beats ( $P = 0.000018$ ) after which the changes in HRR<sub>HIT</sub> tended to plateau.

**Table 3.3** Heart rate recovery after each of the eight high intensity training sessions ( $HRR_{HIT}$ ). Data ( $X \pm s$ ) are expressed as change in heart rate within the first 60s after completing the HIT sessions and the difference in HRR compared to session 1. (n= 14)

HIT session	1	2	3	4	5	6	7	8
$HRR_{HIT}$ (beats)	$36 \pm 8$	$38 \pm 9$	$39 \pm 9$	$40 \pm 9$	$42 \pm 8^{\#}$	$43 \pm 9^{\$}$	$43 \pm 8^{\$}$	$43 \pm 8^{\$}$
Difference vs. session 1 (beats)	$0 \pm 0$	$2 \pm 3$	$3 \pm 5$	$5 \pm 3$	$5 \pm 5$	$7 \pm 4$	$6 \pm 4$	$7 \pm 6$

$^{\#} P < 0.01$ ,  $^{\$} P < 0.001$  when compared to training session 1

## DISCUSSION

This is the first study to investigate changes in HRR during and after 4 weeks of HIT in a group of well-trained cyclists. The results show that all cyclists responded well to the HIT protocol with a significant improvement in all performance parameters, except for  $VO_{2max}$ . These improvements in performance parameters are in accordance with other studies, using similar training protocols, that have shown the benefits of HIT in well and highly trained cyclists (Laursen *et al.* 2002; Laursen and Jenkins 2002; Stepto *et al.* 1999). This finding confirms that the HIT protocol used in this study was correctly implemented.

### HIT and $HRR_{40km}$

The main finding from this study was that  $HRR_{40km}$  improved ( $6 \pm 3$  beats) after 4 weeks of HIT in a group of well-trained cyclists. This finding, is in accordance with the data of Buchheit *et al.* (2008), who showed a similar magnitude of change in HRR in a group of fit adolescents, who also participated in a HIT program. The change in HRR after HIT was less than the value which we regarded as meaningful when we calculated the sample size (9 beats) in planning the study (Lamberts *et al.* 2004). The original assumption however was formed from data using a different protocol with a different exercise intensity and duration prior to the measurement of recovery heart rate, which could have influenced the day-to-day variation in heart rate. We performed a post-study power analysis (Altman 1991) to confirm if the magnitude of change in  $HRR_{40km}$  could be considered real. This calculation revealed a 100 percent power at a 5% significant level, which confirms that we were not making a type II error. These findings suggest that relatively small changes in recovery heart rate can

be measured in a group of already well-trained cyclist. However this is only true if the same level of control is used when performing the testing protocol.

### **HRR<sub>40km</sub> and change in performance parameters**

The second important finding of this study was that the improvements in HRR<sub>40km</sub> correlate well with some improvements in performance parameters. For example, about 93% of the variation in the improvements in HRR<sub>40km</sub> ( $r = 0.96$ ) could be accounted for by the variation in the improvement in 40km TT time. A weaker correlation was found between the variation in the improvements in PPO, which could only account for about 54% of the change in HRR<sub>40km</sub> ( $r = 0.73$ ). The stronger correlation between HRR<sub>40km</sub> and 40km TT time might be explained by the fact that HRR<sub>40km</sub> was directly measured after the 40km TT and is therefore more closely related to 40km TT performance. These findings, are similar to a study which found a correlation ( $r = 0.62$ ) between change in indices of HRR and improvements in repeated-sprint ability (Buchheit *et al.* 2008). The lack of relationship between change in HRR<sub>40km</sub> and change in VO<sub>2max</sub> is not novel (Buchheit and Gindre 2006), and confirms that VO<sub>2max</sub> is of limited value in tracking or predicting athletic ability (Lamberts *et al.* 2009; Noakes 2008).

### **HIT and HRR<sub>HIT</sub>**

The third finding of this study was that HRR<sub>HIT</sub> improved throughout the HIT sessions. The first significant differences in HRR<sub>HIT</sub> (compared to the values of the first training session) occurred after the 5<sup>th</sup> HIT session ( $5 \pm 5$  beats) and kept on improving until the 8<sup>th</sup> and final HIT session ( $7 \pm 6$  beats).

### **HRR<sub>40km</sub> and HRR<sub>HIT</sub>**

Although HRR<sub>40km</sub> and HRR<sub>HIT</sub> improved similarly over the training period, the HRR was faster after the HIT sessions when compared to the 40km TT ( $P = 0.0118$ ). This is in accordance with Kaikonen *et al.* (2008) who recently reported a faster HRR after a similar interval training protocol (7 times 3 minute exercise at 85% of VO<sub>2max</sub>, with 2 minute rest intervals) compared to a continuous protocol at the same intensity and duration.

Factors that have shown to influence autonomic nervous system response after exercise, measured through HRV, are the mode of exercise (Heffernan *et al.* 2006), the proceeding workload intensity (Kaikkonen *et al.* 2008) and duration (Seiler *et al.* 2007). As HRR after moderate to heavy exercise is a consequence of parasympathetic reactivation and sympathetic withdrawal (autonomic nervous system), HRR responses in this study might also have been influenced by the intensity at the end of the proceeding workload (after the interval training or 40km TT). A recent study showed that recovery after maximal exercise is mainly caused by parasympathetic reactivation where sympathetic activation can even carry on into the early phases of recovery (Kannankeril *et al.* 2004). As subjects sprinted during the last kilometre of the 40km TT, in an attempt to set the fastest possible time, sympathetic drive was further stimulated. Therefore  $HRR_{40km}$  was measured from an intensity of  $98 \pm 2\%$  of  $HR_{max}$ . This higher intensity compared to an intensity of  $93 \pm 2\%$  of  $HR_{max}$  after  $HRR_{HIT}$  might also have contributed to the slower  $HRR_{40km}$  compared to the  $HRR_{HIT}$ . A third contributing factor might have been the duration of cycling at high intensities which was  $\pm 65$  minute for the 40km TT and 32 minute (8 X 4 minute) per HIT session.

The reason for this study was to determine if changes in HRR were sufficiently sensitive to track changes in performance in already well-trained cyclists. As HRR after exercise is an easy and non-invasive method to collect data representing the functioning of the autonomic nervous system, and appears to be sensitive to direct changes in training markers, HRR can possibly play an important role in prescribing and fine tuning training (Borresen and Lambert 2008; Buchheit *et al.* 2007; Lamberts and Lambert 2009). However, it is recommended that HRR needs to be measured after a standardised test, as factors of duration, intensity an exercise mode influence the rate of HRR.

In conclusion, this study to shows that HRR changes in a group of already well-trained cyclists who improved their performance parameters after a period of HIT. The changes in  $HRR_{40km}$  were associated with changes in 40km TT time (s) and relative peak power ( $W \cdot kg^{-1}$ ). This relationship indicates that  $HRR_{40km}$  and possibly HRR measured after a standardised warming up period, may be a sensitive

monitoring tool to track changes in performance parameters in already well-trained cyclist.

### **ACKNOWLEDGEMENTS**

The authors would like to thanks all cyclists who participated in this study. This study was funded by the van Ewijck foundation, the Medical Research Council of South Africa, Discovery Health and the University of Cape Town.

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## REFERENCES

- Altman DG (1991) Practical Statistics for Medical Research. Chapman and Hall, London, UK.
- American College of Sports Medicine (2007) Submaximal Exercise Tests. In: Whaley MH, Brubaker PH and Otto RM. (eds) ACSM's Guidelines for Exercise Testing and Prescription. Lippincott Williams & Wilkins, pp 70-74.
- Baumert M, Brechtel L, Lock J, Hermsdorf M, Wolff R, Baier V and Voss A (2006) Heart rate variability, blood pressure variability, and baroreflex sensitivity in overtrained athletes. Clin J Sport Med 16: 412-417
- Boas EP (1931) The heart rate of boys during and after exhausting exercise. J Clin Invest 10: 145-152
- Borresen J and Lambert MI (2007) Changes in heart rate recovery in response to acute changes in training load. Eur J Appl Physiol 101: 503-511
- Borresen J and Lambert MI (2008) Autonomic control of heart rate during and after exercise - measurements and implications for monitoring training status. Sports Med 28: 633-646
- Buchheit M and Gindre C (2006) Cardiac parasympathetic regulation: respective associations with cardiorespiratory fitness and training load. Am J Physiol Heart Circ Physiol 291: H451-H458

Buchheit M, Millet GP, Parisy A, Pourchez S, Laursen PB and Ahmaidi S (2008) Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Med Sci Sports Exerc* 40: 362-371

Buchheit M, Papelier Y, Laursen PB and Ahmaidi S (2007) Noninvasive assessment of cardiac parasympathetic function: postexercise heart rate recovery or heart rate variability? *Am J Physiol Heart Circ Physiol* 293: H8-H10

Bunc V, Heller J and Leso J (1988) Kinetics of heart rate responses to exercise. *J Sports Sci* 6: 39-48

Cole CR, Blackstone EH, Pashkow FJ, Snader CE and Lauer MS (1999) Heart-rate recovery immediately after exercise as a predictor of mortality. *N Engl J Med* 341: 1351-1357

Davison RCR, Corbett J and Ansley L (2007) Influence of temperature and protocol on the calibration of the computrainer electromagnetically braked cycling ergometer. *J of Sports Sci* 25: 257-258

Durnin JVGA and Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr* 32: 77-97

Gnehm P, Reichenbach S, Altpeter E, Widmer H and Hoppeler H (1997) Influence of different racing positions on metabolic cost in elite cyclists. *Med Sci Sports Exerc* 29: 818-823

Hawley JA and Noakes TD (1992) Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur J Appl Physiol Occup Physiol* 65: 79-83

Hedelin R, Kenttä G, Wiklund U, Bjerle P and Henriksson-Larsen K (2000) Short-term overtraining: effects on performance, circulatory responses, and heart rate variability. *Med Sci Sports Exerc* 32: 1480-1484

Heffernan KS, Kelly EE, Collier SR and Fernhall B (2006) Cardiac autonomic modulation during recovery from acute endurance versus resistance exercise. *Eur J Cardiovasc Prev Rehabil* 13: 80-86

Jeukendrup A (2002) High-performance cycling. Human Kinetics Publishers, Inc., Champaign, IL, USA.

Jeukendrup AE, Craig NP and Hawley JA (2000) The bioenergetics of World Class Cycling. *J Sci Med Sport* 3: 414-433

Kaikkonen P, Rusko H and Martinmaki K (2008) Post-exercise heart rate variability of endurance athletes after different high-intensity exercise interventions. *Scand J Med Sci Sports* 18: 511-519

Kannankeril PJ, Le FK, Kadish AH and Goldberger JJ (2004) Parasympathetic effects on heart rate recovery after exercise. *J Investig Med* 52: 394-401



Kenttä G and Hassmén P (1998) Overtraining and recovery. A conceptual model.  
Sports Med 26: 1-16

Kiviniemi AM, Hautala AJ, Kinnunen H and Tulppo MP (2007) Endurance training  
guided individually by daily heart rate variability measurements. Eur J  
Appl Physiol 101: 743-751

Kuipers H (1998) Training and overtraining: an introduction. Med Sci Sports Exerc  
30: 1137-1139

Lambert MI and Borresen J (2006) A theoretical basis of monitoring fatigue: a  
practical approach for coaches. International Journal of Sports Science  
& Coaching 1: 371-388

Lamberts RP and Lambert MI (2009) Day-to-day variation in heart rate at different  
levels of submaximal exertion: implications for monitoring training. J  
Strength Cond Res 23: 1005-1010

Lamberts RP, Lemmink KA, Durandt JJ and Lambert MI (2004) Variation in heart rate  
during submaximal exercise: implications for monitoring training. J  
Strength Cond Res 18: 641-645

Lamberts RP, Swart J, Woolrich RW, Noakes TD and Lambert MI (2009)  
Measurement error associated with performance testing in well-trained  
cyclists; application to the precision of monitoring changes in training  
status. International SportMed Journal 10: 33-44

Laursen PB and Jenkins DG (2002) The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Med* 32: 53-73

Laursen PB, Shing CM, Peake JM, Coombes JS and Jenkins DG (2002) Interval training program optimization in highly trained endurance cyclists. *Med Sci Sports Exerc* 34: 1801-1807

Lehmann M, Foster C, Dickhuth HH and Gastmann U (1998) Autonomic imbalance hypothesis and overtraining syndrome. *Med Sci Sports Exerc* 30: 1140-1145

Lehmann MJ, Lormes W, Opitz-Gress A, Steinacker JM, Netzer N, Foster C and Gastmann U (1997) Training and overtraining: an overview and experimental results in endurance sports. *J Sports Med Phys Fitness* 37: 7-17

Lucia A, Hoyos J, Santalla A, Perez M and Chicharro JL (2002a) Kinetics of  $\text{VO}_2$  in professional cyclists. *Med Sci Sports Exerc* 34: 320-325

Lucia A, Rivero JL, Perez M, Serrano AL, Calbet JA, Santalla A and Chicharro JL (2002b) Determinants of  $\text{VO}_2$  kinetics at high power outputs during a ramp exercise protocol. *Med Sci Sports Exerc* 34: 326-331

- Meeusen R, Duclos M, Gleeson M, Rietjens GJ, Steinacker JM and Urhausen A (2006) Prevention, diagnosis and treatment of the overtraining syndrome. *European Journal of Sports Science* 6: 1-14
- Mujika I and Padilla S (2001) Physiological and performance characteristics of male professional road cyclists. *Sports Med* 31: 479-487
- Noakes TD (2008) Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *Br J Sports Med* 42: 551-555
- Padilla S, Mujika I, Orbananos J and Angulo F (2000) Exercise intensity during competition time trials in professional road cycling. *Med Sci Sports Exerc* 32: 850-856
- Ross WD and Marfell-Jones MJ (1991) Kinanthropometry. In: MacDougall JD, Wenger HA and Green HS. (eds) *Physiological Testing of the High Performance Athlete*. Champaign, IL: Human Kinetics, pp 223-308.
- Seiler S, Haugen O and Kuffel E (2007) Autonomic recovery after exercise in trained athletes: intensity and duration effects. *Med Sci Sports Exerc* 39: 1366-1373
- Shepley B, MacDougall JD, Cipriano N, Sutton JR, Tarnopolsky MA and Coates G (1992) Physiological effects of tapering in highly trained athletes. *J Appl Physiol* 72: 706-711

- Shetler K, Marcus R, Froelicher VF, Vora S, Kalisetti D, Prakash M, Myers J and Do D (2001) Heart rate recovery: Validation and methodologic issues. *J Am Coll Cardiol* 38: 1980-1987
- Short KR and Sedlock DA (1997) Excess postexercise oxygen consumption and recovery rate in trained and untrained subjects. *J Appl Physiol* 83: 153-159
- Solberg G, Robstad B, Skjønsberg OH and Borchsenius F (2005) Respiratory gas exchange indices for estimating the anaerobic threshold. *J Sports Sci Med* 4: 29-36
- Stephens NK, Hawley JA, Dennis SC and Hopkins WG (1999) Effects of different interval-training programs on cycling time-trial performance. *Med Sci Sports Exerc* 31: 736-741
- Sugawara J, Murakami H, Maeda S, Kuno S and Matsuda M (2001) Change in post-exercise vagal reactivation with exercise training and detraining in young men. *Eur J Appl Physiol* 85: 259-263
- Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996) Heart rate variability: standards of measurement, physiological interpretation and clinical use. *Circulation* 93: 1043-1065

Yamamoto K, Miyachi M, Saitoh T, Yoshioka A and Onodera S (2001) Effects of endurance training on resting and post-exercise cardiac autonomic control. Med Sci Sports Exerc 33: 1496-1502

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# Chapter 4

**Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. \***

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## ABSTRACT

Determining the optimal balance between training load and recovery contributes to peak performance in well-trained athletes. The measurement of heart rate recovery (HRR) to monitor this balance has become popular. However, it is not known whether the impairment in performance, which is associated with training-induced fatigue, is accompanied by a change in HRR. Therefore, the aim of this study was to retrospectively analyse the relationship between changes in HRR and cycling performance in a group of well-trained cyclists ( $n = 14$ ) who participated in a 4 week high intensity training (HIT) program. Subjects were assigned to either a group that had a continuous increase their HRR ( $G_{Incr}$ ) or a group that had a decrease in HRR ( $G_{Decr}$ ) during the HIT period. Both groups,  $G_{Incr}$  and  $G_{Decr}$ , had improvements in relative peak power output ( $P = 0.001$  and  $P = 0.016$ , respectively), and endurance performance parameters ( $P = 0.001$  and  $P < 0.048$ , respectively). Average power during the 40km TT however improved more in  $G_{Incr}$  ( $P = 0.010$ ) resulting in a tendency for a faster 40km TT time ( $P = 0.059$ ). These findings suggest that HRR has the potential to monitor changes in endurance performance and contribute to a more accurate prescription of training load in well-trained and elite cyclists.

### Keywords:

Cycling • Monitoring • Overreaching • Performance • Adaptation • Recovery • Overtraining • Autonomic nervous system

## INTRODUCTION

Well-trained and elite cyclists need to be exposed to maximal effective training loads followed by a minimal, but sufficient recovery period between each training session to achieve peak performances. Such a training program should prevent under-training and over-training (Meeusen *et al.* 2006), and result in a predictable progression of training adaptations and the ability to reach peak performance at the appropriate time.

To facilitate the development of such a training program, a variety of monitoring tools have been developed to track changes in training status (Lambert and Borresen 2006). Most of these monitoring tools aim to measure the overall well-being of the athlete in response to the applied training load. Examples of these measurement tools are the Profile of Mood Status (POMS) questionnaire (McNair *et al.* 1971), the Daily Analysis of Life Demands for Athletes (DALDA) questionnaire (Rushall 1990) and Kenttä's passive and/or active recovery scale (Kenttä and Hassmén 1998). Another more direct method is to assess the responsiveness of the athlete's autonomic nervous system following a training stimulus. The autonomic nervous system consists of parasympathetic and sympathetic components and is interlinked with many other physiological systems (Borresen and Lambert 2008; Kiviniemi *et al.* 2007). The responsiveness of the autonomic nervous system may therefore provide useful information about the functional adaptations of the human body. Techniques used to measure the responsiveness of the autonomic nervous system include the measurement of heart rate variability (HRV) (Buchheit *et al.* 2007b; Buchheit *et al.* 2008; Kaikkonen *et al.* 2008) and heart rate recovery (HRR) (Buchheit *et al.* 2007b; Lamberts *et al.* 2004; Lamberts *et al.* 2009a). Interestingly, Buchheit *et al.* (2007b; 2008) recently concluded that indices of HRR seem to be a more sensitive marker of recently applied training loads compared to indices of HRV, which reflect a long term modulation of the autonomic nervous system with changes in training status.

This is supported by a recent study which showed that HRR decreased less following a controlled bout of submaximal exercise in a group of trained runners who suddenly increased their training load by 55% (Borresen and Lambert 2007). This response was interpreted as representing a negative training response to the sudden increase



in training load. Unfortunately performance parameters were not measured in this study to verify whether the negative training effect was associated with an impairment in performance. This is an important question as a better understanding of any association between a negative training effect and impaired performance has potential practical implications.

Accordingly, the aim of this study was to monitor the relationship between HRR after exercise and cycling performance in a group of well-trained cyclists who participated in a 4 week high intensity training program (HIT) program. Due to the nature of study we chose to measure HRR directly after the HIT session, as earlier described by Buchheit *et al.* (2007a), and expected that symptoms of fatigue and an associated impaired performance would manifest in some of the participating cyclists. We hypothesised that HRR after exercise would improve in those cyclists that were able to tolerate the training load, whereas cyclists who were not able showed signs of being unable to tolerate the training load would show a decrease in HRR associated with a blunted improvement in performance parameters.

## METHODS

### ***Recruitment***

The data of fourteen well-trained male cyclists who successfully completed a 4 week HIT period was part of a larger study of which a part has already been published (Lamberts *et al.* 2009a). However whereas that study focused on changes in HRR after the 40km TT ( $HRR_{40km}$ ) before and after the HIT training period, the current study focuses on changes in HRR after each HIT session ( $HRR_{HIT}$ ) during the HIT training period.

The characteristics of the subjects are presented in Table 4.1. All subjects had a minimal training load of 6 hours per week with at least 3 years of cycling experience and were classified as well-trained (Jeukendrup 2002). Prior to the start of the study subjects completed a Physical Activity Readiness Questionnaire (PAR-Q) (American College of Sports Medicine 2007), were personally interviewed about their training history and signed an informed consent after they were informed about the risks and

stresses associated with the research protocol. The study was approved by the Ethics and Research Committee of the Faculty of Health Sciences of the University of Cape Town. The principles outlined by the Declaration of Helsinki for the Use of Humans were adopted in this study (2002).

During all performance tests and training sessions heart rate was recorded continuously at a capturing rate of 34 Hz by the Computrainer™ software. HRR after the HIT sessions ( $HRR_{HIT}$ ) was also recorded with the Computrainer™ software. HRR was calculated as described previously (Borresen and Lambert 2007; Lamberts *et al.* 2004) and defined as the reduction in heart rate within the first 60 seconds after the cessation of the 8<sup>th</sup> interval of an HIT session ( $HRR_{HIT}$ ) (Lamberts *et al.* 2009a). In an attempt to control factors which could influence heart rate and HRR, subjects were asked to sit passively and straight up on their cycles (Gnehm *et al.* 1997), to remain still and not talk during the recovery period.

After the training programme the HRR were analysed and subjects were assigned to either a continuous increasing HRR group ( $G_{Incr}$ ) or a group that showed a decrease in HRR ( $G_{Decr}$ ) after exercise during the training period. The minimal sample size for this study was determined using the 40km time trial data from Palmer *et al.* (1996). Assuming the smallest meaningful difference in performance is 1.0%, with a standard deviation of 0.5%, the sample size required for this study, to achieve a statistical power of 80% and a significance level of 5%, was therefore  $n = 5$  for each group (Altman 1991).

### **Identifying $G_{Incr}$ and $G_{Decr}$**

After the completion of study, which included all training sessions and performance testing (pre and post), each individual  $HRR_{HIT}$  pattern was analysed retrospectively. Based on this pattern cyclists were assigned to either a group which showed a continuous increase in  $HRR_{HIT}$  ( $G_{Incr}$ ) (faster) or a group that showed a decrease in  $HRR_{HIT}$  ( $G_{Decr}$ ) (slower) during the HIT period. An a priori determined inclusion criteria for  $G_{Decr}$  was defined as at least 2 consecutive decreases in  $HRR_{HIT}$  during the HIT period. In contrast all cyclists in  $G_{Incr}$  had to show a continuous increase in  $HRR_{HIT}$ . A once off decrease or unchanged  $HRR_{HIT}$  in  $G_{Incr}$  was considered as an effect of an 'off day' and therefore found acceptable for the inclusion into  $G_{Incr}$ .

### **Study design**

A week before the testing and training period the subjects performed a 40km familiarization time trial on an electronically braked cycle ergometer (Computrainer™ Pro 3D, RacerMate, Seattle, WA, USA) over a flat course, as previously described (Lamberts *et al.* 2009a).

Three days before the start of the training period all subjects performed a peak power output test (PPO), which included respiratory gas analysis for measurement of maximal oxygen consumption ( $\text{VO}_{2\text{max}}$ ), followed by a 40km time trial (40km TT) one day before the start of the training period. After completing the initial tests, subjects started their 4 week training protocol which consisted of two HIT sessions, two 90 minute recovery rides below lactate threshold (Solberg *et al.* 2005) and three rest days each week. During all testing and training sessions subjects were blinded to any feedback of time, power output, heart rate and speed to prevent them from adopting a pacing strategy and possibly biasing the performance outcomes. The only exception to this was the display of completed distance during the 40km TT. Additionally subjects were asked to avoid participating in any racing or prolonged or high intensity exercise during the study. Each subject was asked to maintain a detailed training diary and to record all heart rate data during all training sessions performed outside of the laboratory for the duration of the study. Subjects were questioned and training logbooks inspected prior to the second testing phase to ensure that they had adhered to the training protocol (Lamberts *et al.* 2009a).

### **Warm-up and calibration.**

Before all testing and training sessions subjects performed a self-paced 15 minute warm-up ride on a simulated 40km flat TT course. Testing and training was done on the subject's own bicycle which was mounted on the Computrainer™ ergometer system (Computrainer™ Pro 3D, RacerMate, Seattle, WA, USA). The system was calibrated as previously described by Lamberts *et al.* (2009a).

All test and training sessions were done under stable climate conditions ( $22.3 \pm 1.3$  °C,  $53.7 \pm 2.4\%$  relative humidity,  $101.9 \pm 0.8$  kPa) and at a similar time of day (within 60 min). Before each testing or training session body mass was measured. Stature and body fat (expressed as a percentage (Durnin and Womersley 1974) and the sum

of seven skinfolds (Ross and Marfell-Jones 1991)) was measured before the start of the 40km TT.

### **Performance tests**

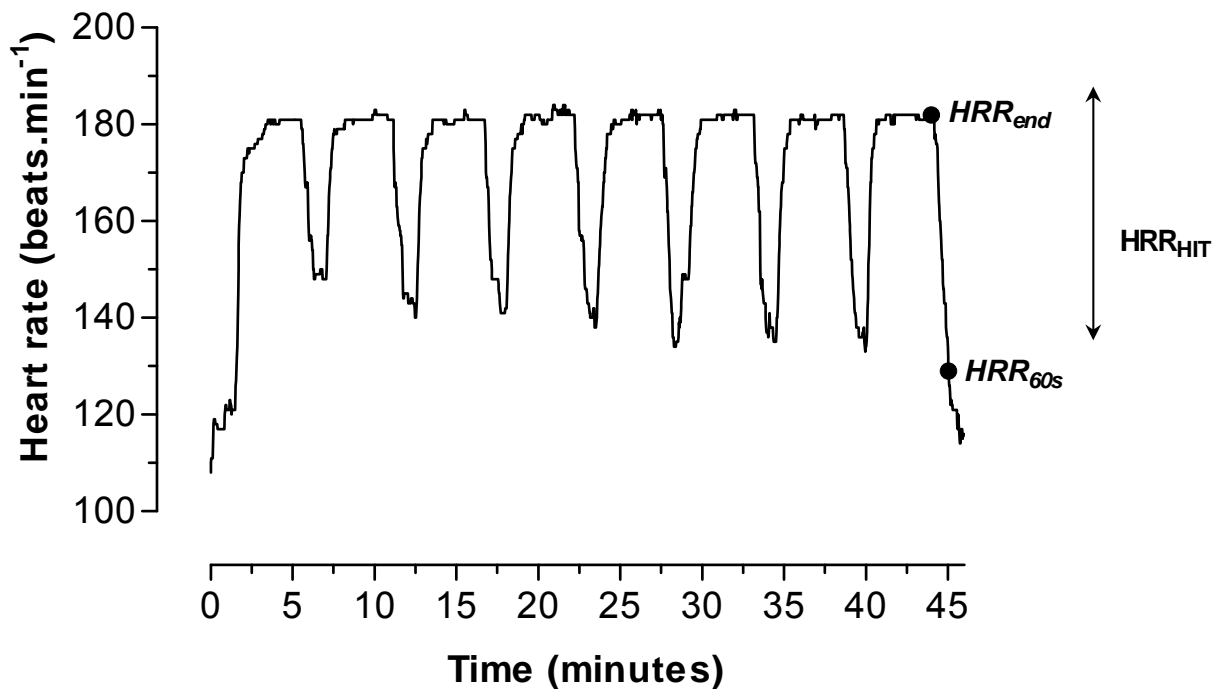
Markers of cycling performance were determined by a peak performance test (PPO including  $\text{VO}_{2\text{max}}$ ) and an endurance cycle test (40km TT) (Hawley and Noakes 1992; Lucia *et al.* 2002b; Lucia *et al.* 2002a; Mujika and Padilla 2001; Padilla *et al.* 2000). These tests were conducted before and after the 28 day training period and a 10 day low intensity taper period. This tapering period allowed the cyclists to recover from their HIT before they were re-tested (Jeukendrup 2002; Shepley *et al.* 1992).

All subjects were asked to perform a 90 minute submaximal recovery ride, below lactate threshold (Solberg *et al.* 2005), 24 hours prior to the performance tests. As previously described (Lamberts *et al.* 2009a), the PPO test was performed at a starting work rate of  $2.50 \text{ W}\cdot\text{kg}^{-1}$  body mass after which the load was increased incrementally by 20 W each minute until the cyclist could not maintain a cadence greater than 70 revolutions per minute (rpm) or was volitionally exhausted. During this test ventilation, oxygen uptake ( $\text{VO}_2$ ) and  $\text{CO}_2$  production ( $\text{VCO}_2$ ) were measured over 15 second intervals using an on-line breath-by-breath gas analyser (Oxycon, Viasis, Hoechberg, Germany). Subjects were verbally encouraged to perform to maximal exhaustion. Maximal peak power output was determined as the mean power output during the final minute of the PPO test whereas  $\text{VO}_{2\text{max}}$  ( $\text{l}\cdot\text{min}^{-1}$ ) was defined as the highest recorded reading over a 30 second period. The 40km TT was performed on a simulated 40km flat time trial course which was programmed into the Computrainer<sup>TM</sup>. Subjects were allowed to drink water *ad libitum* throughout the test and were given clear instructions to complete the 40km distance in the fastest possible time. All subjects refrained from consuming any food and caffeine for 2 and 3 hours respectively, prior to all performance testing and training sessions.

### **Training sessions**

All subjects followed the same structured training program which included HIT sessions, rest days and recovery rides. Each HIT session consisted of 8 intervals at approximately 80% of peak power output, determined for each subject during the initial PPO test. Each interval had a duration of 4 minute and was followed by a 90

second self paced recovery period (see also Figure 4.1). All HIT sessions were closely supervised while speed ( $\text{km}\cdot\text{h}^{-1}$ ), power output (W), cadence (rpm) and heart rate ( $\text{beats}\cdot\text{min}^{-1}$ ) were captured at a rate of 34 Hz, as previously described by Lamberts *et al.* (2009a).



**Figure 4.1** The average heart rate response of an arbitrary subject undergoing 8 high intensity periods within a HIT session.  $HRR_{end}$  represents the start of the heart rate recovery measurement ( $HRR_{HIT}$ ).  $HRR_{60s}$  represents the end of the heart rate recovery measurement ( $HRR_{HIT}$ ).  $HRR_{HIT}$  was calculated as the difference between  $HRR_{end}$  and  $HRR_{60s}$ .

### Data analysis

Analysis of performance and training data were performed using CyclingPeaks<sup>TM</sup> analysis software (WKO+ edition, Version 2.1, 2006, Lafayette, CO, USA) and the Computrainer<sup>TM</sup> coaching software (Version 1.5.308, RacerMate, Seattle, USA). Data were expressed as absolute values whereas changes in performance parameters were expressed in absolute and relative (percentages) values. Percentage change was calculated as:

$$\text{Percentage change} = \frac{(\text{Post training session value} - \text{pre training session value})}{(\text{Pre training session value})} \times 100$$

Heart rate data were analysed with CyclingPeaks™ analysis software and Polar precision performance software (Version 4.03.049, Polar Electro, Kempele, Finland).

### **Statistical Analysis**

The data were analysed with STATISTICA version 7.0 (Stat-soft Inc., Tulsa, OK, USA) for any statistical significance ( $P < 0.05$ ). All data are expressed as means  $\pm$  standard deviation ( $X \pm s$ ). An independent T-test by groups was used to determine any differences in general characteristics between  $G_{Incr}$  and  $G_{Decr}$  and relative changes (%) between groups. A two-way analysis of variance (ANOVA) with repeated measures was used to determine differences between the groups for changes in performance parameters ( $VO_{2max}$  (absolute and relative), PPO (absolute and relative), 40km TT time, average power during the 40km TT (absolute and relative)) and  $HRR_{HIT}$  over the 8 HIT sessions. Where a significant difference was found for either main effect (Group or Time), or the interaction between Time X Group, a Tukey *post-hoc* analysis was performed. A significant interaction (Group X Time) was interpreted as meaning that the groups responded differently over time during the training period for that variable. Effect sizes were calculated as the difference between the means divided by the mean standard deviation to characterise the practical (clinical) significance rather than the statistical significance. The following criteria for effect sizes were used:  $<0.1 = \text{trivial}$ ,  $0.1 - 0.3 = \text{trivial/small}$ ,  $0.3 - 0.5 = \text{small}$ ,  $0.5 - 0.7 = \text{small/moderate}$ ,  $0.7 - 1.1 = \text{moderate}$ ,  $1.1 - 1.3 = \text{moderate/large}$ ,  $1.3 - 1.9 = \text{large}$ ,  $1.9 - 2.1 = \text{large/very large}$  and  $>2.1 = \text{very large}$ , which was adapted from Hopkins criteria in SportsScience 6 (available at: <http://www.sportsci.org/jour/0201/wghprob.htm>). Differences in percentage change in performance parameters were determined with an independent T-test. Relationships between changes in performance parameters and changes in  $HRR_{HIT}$  were established using a Pearson's Product moment correlation (GraphPad Prism version 3.00 for Windows, GraphPad Software, San Diego, California, USA). Confidence intervals (95% CI) for the correlations were calculated using a spreadsheet designed for this purpose and downloaded from [www.sportsci.org](http://www.sportsci.org).

## RESULTS

The 14 cyclists who completed the high intensity training programme were retrospectively allocated to either  $G_{Incr}$  ( $n = 8$ ) or  $G_{Decr}$  ( $n = 6$ ). The general characteristics of  $G_{Incr}$  and  $G_{Decr}$  are shown in Table 4.1.

**Table 4.1** General characteristics of the group  $G_{Incr}$  and group  $G_{Decr}$ , expressed as  $X \pm s$ .

Variable	$G_{Incr}$ ( $n = 8$ )	$G_{Decr}$ ( $n = 6$ )
Age (years)	$34 \pm 4^a$	$25 \pm 5^a$
Stature (cm)	$182 \pm 3$	$176 \pm 9$
Body mass (kg)	$76.9 \pm 7.7^b$	$68.5 \pm 6.0^b$
Fat (%)	$16.0 \pm 3.5^c$	$11.7 \pm 2.0^c$
Sum of skinfolds (mm)	$63.8 \pm 23.0$	$49.8 \pm 6.1$
Years of competitive cycling (years)	$13 \pm 7$	$8 \pm 5$
Training hours per week (hours)	$10 \pm 5$	$13 \pm 2$

<sup>a</sup>  $P = 0.003$ , <sup>b</sup>  $P = 0.049$ , <sup>c</sup>  $P = 0.021$

Subjects in  $G_{Incr}$  were significantly older, heavier and had a higher percentage of body fat than  $G_{Decr}$ . The absolute PPO, 40km TT performance and  $VO_{2max}$  values were similar between groups. However, when these were expressed relative to body mass  $VO_{2max}$  ( $P = 0.047$ ), PPO ( $P = 0.016$ ) and average power during the 40km TT ( $P = 0.039$ ) were higher in  $G_{Decr}$ . (Table 4.2).

**Table 4.2** Performance parameters before and after the high intensity training period in both groups ( $G_{Incr}$  and  $G_{Decr}$ ), expressed as  $X \pm s$ .

Variable	$G_{Incr}$		$G_{Decr}$	
	Before	After	Before	After
$VO_{2max}$ ( $l \cdot min^{-1}$ )	$4.3 \pm 0.4$	$4.4 \pm 0.4$	$4.5 \pm 0.6$	$4.5 \pm 0.7$
$VO_{2max}$ ( $ml \cdot kg^{-1} \cdot min^{-1}$ )	$56.5 \pm 5.1$	$58.5 \pm 5.2$	$65.3 \pm 6.7$	$65.9 \pm 5.8$
Peak power output (W)	$375 \pm 30^a$	$391 \pm 34^a$	$377 \pm 39$	$388 \pm 39$
Relative peak power ( $W \cdot kg^{-1}$ )	$4.9 \pm 0.5^b$	$5.2 \pm 0.5^b$	$5.5 \pm 0.5^c$	$5.7 \pm 0.5^c$
40km TT time (40km TT) (min.s)**	$66.17 \pm 2.09^d$	$64.26 \pm 1.51^d$	$64.51 \pm 2.46^e$	$63.58 \pm 2.26^e$
Power during 40km TT (W)*	$251 \pm 22^f$	$271 \pm 21^f$	$260 \pm 32^g$	$270 \pm 29^g$
Rel. power during 40km TT ( $W \cdot kg^{-1}$ )	$3.3 \pm 0.4^h$	$3.6 \pm 0.4^h$	$3.8 \pm 0.3^i$	$3.9 \pm 0.3^i$

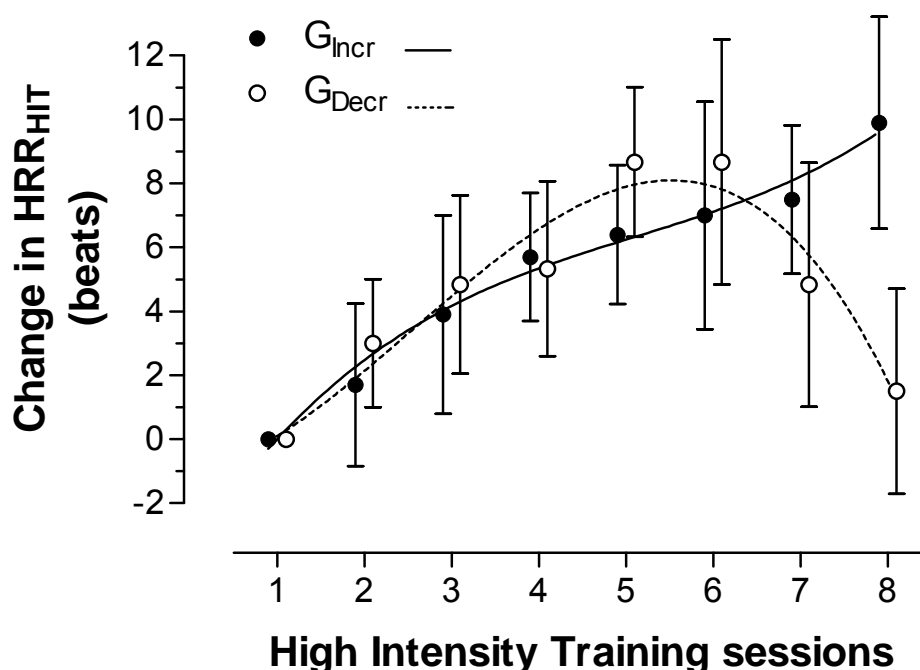
<sup>a</sup>  $P = 0.008$ , <sup>b</sup>  $P = 0.001$ , <sup>c</sup>  $P = 0.016$ , <sup>d</sup>  $P = 0.001$ , <sup>e</sup>  $P = 0.028$ , <sup>f</sup>  $P = 0.001$ , <sup>g</sup>  $P = 0.013$ , <sup>h</sup>  $P = 0.001$ , <sup>i</sup>  $P = 0.048$

\* Group X Time effect  $P = 0.010$ , \*\* Group X Time effect  $P = 0.058$  (trend, not significant)

Analysis of mean heart rate and power during the HIT sessions revealed that both groups trained at the same intensity ( $G_{Incr}$   $78 \pm 2\%$  of PPO and  $89 \pm 2\%$  of  $HR_{max}$ ;  $G_{Decr}$   $79 \pm 1\%$  of PPO and  $89 \pm 2\%$   $HR_{max}$  )

### ***HRR<sub>HIT</sub> patterns of $G_{Incr}$ and $G_{Decr}$***

The exercise intensity (expressed as  $\%HR_{max}$ ) at the end of each HIT session, remained constant in both groups throughout the study ( $G_{Incr}$   $94 \pm 2\%$  vs.  $G_{Decr}$   $93 \pm 2\%$ ). As  $HRR_{HIT}$  may be influenced by exercise intensity, this indicates that any change in  $HRR_{HIT}$  could not be attributed to this methodological point. The changes in  $HRR_{HIT}$  for  $G_{Incr}$  and  $G_{Decr}$  after the 8 HIT sessions are shown in Figure 4.2.  $HRR_{HIT}$  in  $G_{Incr}$  improved throughout the HIT sessions and by the 4<sup>th</sup> HIT session was significantly higher than  $HRR_{HIT}$  after the initial HIT session ( $34 \pm 9$  vs.  $40 \pm 9$  beats;  $P = 0.006$ ). The largest improvement of  $11 \pm 1$  beats ( $P = 0.001$ ) for  $G_{Incr}$  was found after the 8<sup>th</sup> HIT session (Table 4.3). Throughout the HIT period all participants within  $G_{Incr}$  showed one day during which HRR was similar or slightly lower than during the previous session.



**Figure 4.2** Changes of  $HRR_{HIT}$  during the 8 HIT sessions in  $G_{Incr}$  (●) and  $G_{Decr}$  (○), expressed as a relative change to the initial heart rate recovery during session 1. ( $X \pm s$ ). A third polynomial regression line ( $y = a + bx + cx^2 + dx^3$ ) for each group (●,  $r = 0.77$ ; ○,  $r = 0.72$ ) over time is drawn to indicate the  $HRR_{HIT}$  pattern.



HRR<sub>HIT</sub> in  $G_{Decr}$  also improved, being significantly higher after the 6<sup>th</sup> HIT session ( $9 \pm 4$  beats) when compared to the initial HIT session ( $39 \pm 6$  vs.  $47 \pm 5$  beats;  $P = 0.001$ ). However, this significant change disappeared during the 7<sup>th</sup> and 8<sup>th</sup> HIT interval.

**Table 4.3** Mean heart rate recovery after each of the 8<sup>th</sup> high intensity training sessions (HRR<sub>HIT</sub>) in  $G_{Incr}$  ( $n = 8$ ) and  $G_{Decr}$  ( $n = 6$ ). Data are expressed  $X \pm s$  in absolute (heart rate at end of the test minus heart rate 60s later (beats)) and relative values (HRR<sub>HIT</sub> - HRR<sub>HIT</sub> during the first HIT session (beats))

HIT session	1	2	3	4	5	6	7	8
$G_{Incr}$								
absolute	$34 \pm 9$	$36 \pm 10$	$38 \pm 11$	$40 \pm 9^*$	$40 \pm 9^*$	$40 \pm 10^*$	$42 \pm 10^{**}$	$46 \pm 9^{**}$
relative	$0 \pm 0$	$2 \pm 3$	$4 \pm 3$	$6 \pm 2$	$6 \pm 2$	$6 \pm 3$	$8 \pm 2$	$11 \pm 1$
$G_{Decr}$								
absolute	$39 \pm 6$	$41 \pm 6$	$39 \pm 8$	$41 \pm 9$	$40 \pm 11$	$47 \pm 5^{**}$	$44 \pm 6$	$40 \pm 6$
relative	$0 \pm 0$	$3 \pm 2$	$3 \pm 3$	$5 \pm 3$	$9 \pm 2$	$9 \pm 4$	$5 \pm 4$	$2 \pm 3$

\*  $p < 0.01$ , \*\*  $p < 0.001$  when compared to training session 1

### Changes in performance parameters

Changes in performance parameters after HIT were calculated and analysed as absolute changes and relative changes expressed as a percentage of the initial value.

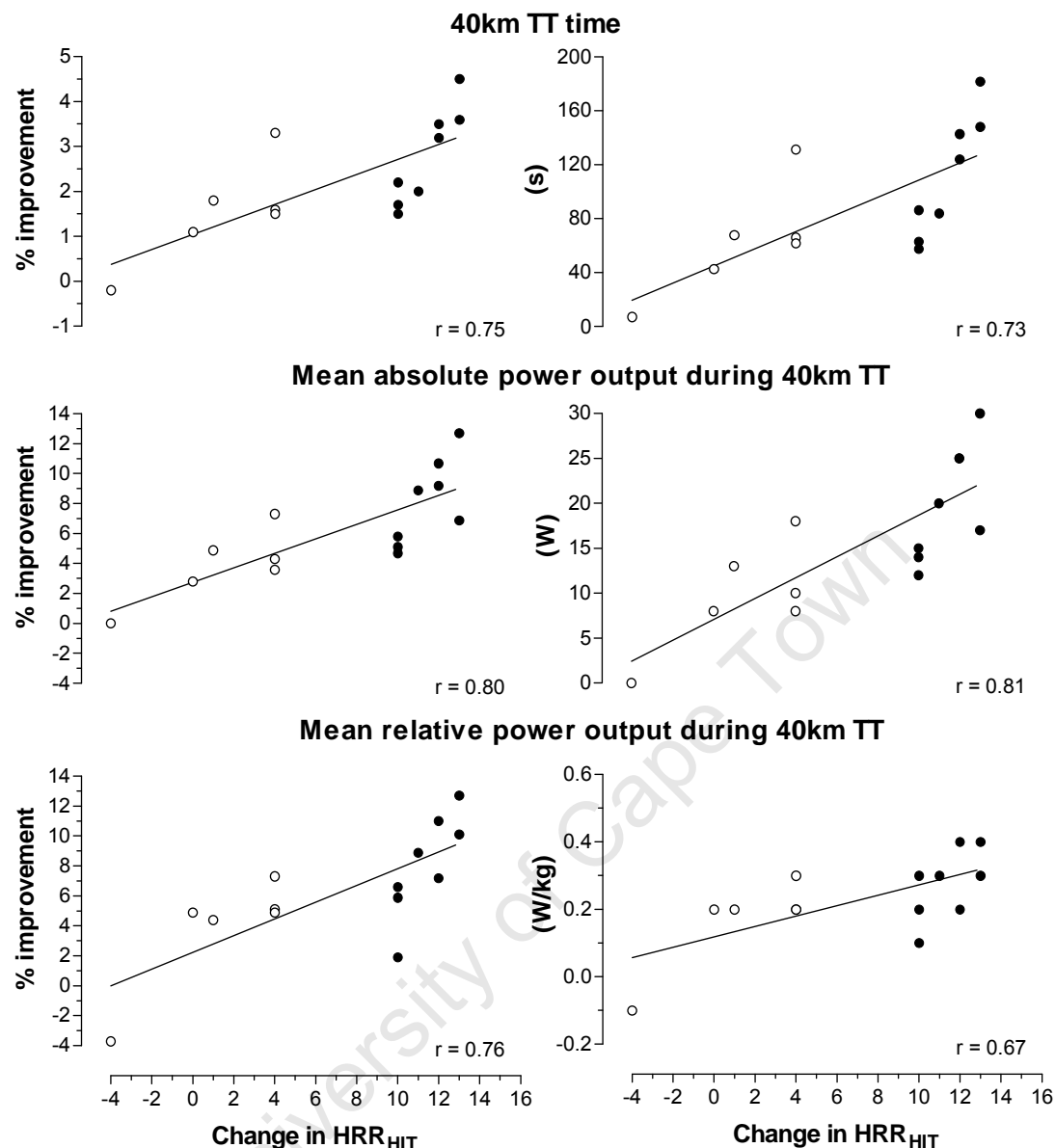
Absolute changes in performance parameters in both groups ( $G_{Incr}$  and  $G_{Decr}$ ) are shown in Table 4.2. Although no significant changes were found for  $VO_{2max}$ , relative PPO ( $W \cdot kg^{-1}$ ) improved in both groups after the training period while, absolute PPO (W) only improved in  $G_{Incr}$ . All endurance performance parameters which were measured during the 40km TT also improved after the training period in both groups (see also Table 4.2). A significant interaction effect of Time X Group was found for average power during the 40km TT ( $P = 0.010$ ). This indicates that average power during the 40km TT improved significantly more in  $G_{Incr}$  than  $G_{Decr}$ . A similar tendency was found for 40km TT time, however this interaction effect was not statistically significant ( $P = 0.059$ ).

**Table 4.4** Absolute and relative changes in performance parameters after the HIT training period, expressed as  $X \pm s$ . Effect size calculated as: (absolute change  $G_{Incr}$  – absolute change  $G_{Decr}$ ) / (mean STDEV of  $G_{Incr}$  and  $G_{Decr}$ )

Variable	$G_{Incr}$		$G_{Decr}$		Difference	Chances that the differences between $G_{Incr}$ and $G_{Decr}$ are truly meaningful	
	Change (absolute)	Change (%)	Change (absolute)	Change (%)	% change <i>P</i> -value	Effect size	Descriptor
$VO_{2max}$ ( $l \cdot min^{-1}$ )	$0.1 \pm 0.2$	$2.5 \pm 4.6$	$0.0 \pm 0.3$	$0.8 \pm 6.1$	0.551	0.33	Small
$VO_{2max}$ ( $ml \cdot kg^{-1} \cdot min^{-1}$ )	$2.1 \pm 2.2$	$3.7 \pm 3.8$	$0.6 \pm 3.1$	$1.1 \pm 4.8$	0.270	0.57	Small / Moderate
Peak power output (W)	$16 \pm 14$	$4.4 \pm 3.8$	$10 \pm 6$	$2.7 \pm 1.6$	0.347	0.60	Small / Moderate
Relative peak power ( $W \cdot kg^{-1}$ )	$0.3 \pm 0.1$	$5.6 \pm 2.8$	$0.2 \pm 0.1$	$3.2 \pm 2.2$	0.113	1.00	Moderate
40km TT time (TT) (min.s)	$-1.51 \pm 0.45$	$-2.8 \pm 1.1^{**}$	$-1.00 \pm 0.45$	$-1.5 \pm 1.1^{**}$	0.058 <sup>**</sup>	1.13	Moderate / Large
Mean power during 40km TT (W)	$20 \pm 6$	$8.0 \pm 2.8^*$	$10 \pm 6$	$3.8 \pm 2.4^*$	0.013 <sup>*</sup>	1.67	Large
Mean relative power during 40km TT ( $W \cdot kg^{-1}$ )	$0.3 \pm 0.1$	$8.0 \pm 3.4^*$	$0.1 \pm 0.1$	$3.8 \pm 3.8^*$	0.049 <sup>*</sup>	2.00	Very large

<sup>\*</sup> $P < 0.05$ , <sup>\*\*</sup> Trend, not significant

Relative changes in performance parameters, (i.e. changes in performance parameters as a percentage from the initial measurement), are shown in Table 4.4. When the data were expressed as a percentage change, no significant changes in any of the peak performance parameters over time were found. In contrast, absolute and relative mean power during the 40km TT (endurance parameters) improved significantly in both groups after the training period. In contrast, there was a tendency for 40km TT time to improve in both groups but this was not significant ( $P = 0.058$ )



**Figure 4.3** Change in  $HRR_{HIT}$  (between the 8<sup>th</sup> and 1<sup>st</sup> HIT session) and change in absolute and relative 40km TT performance parameters in  $G_{Incr}$  (●) and  $G_{Decr}$  (○).

***Relationships between the change in  $HRR_{HIT}$  and 40km TT performance parameters.***

There were significant relationships between the change in  $HRR_{HIT}$  and changes in absolute and relative 40km TT performance parameters (Figure 4.3).

Changes in  $HRR_{HIT}$  had the strongest relationship with the change in mean absolute power when expressed either as a absolute (W) or relative value (%) ( $r = 0.81$ ; 95% CI: 0.49 to 0.94 ( $P = 0.001$ ) and  $r = 0.80$ ; 95% CI: 0.47 to 0.93 ( $P =$

0.001), respectively). A weaker relationship was found between changes in  $HRR_{HIT}$  and the change in relative mean power, both expressed as absolute ( $W \cdot kg^{-1}$ ) ( $r = 0.67$ ; 95% CI: 0.22 to 0.89;  $P = 0.008$ ) or relative (%) value ( $r = 0.76$ ; 95% CI: 0.38 to 0.92;  $P = 0.002$ ). Relationships of  $r = 0.73$  (95% CI: 0.33 to 0.91;  $P = 0.003$ ) and  $r = 0.75$  (95% CI: 0.36 to 0.92;  $P = 0.002$ ) were found between  $HRR_{HIT}$  and absolute and relative 40km TT improvement, respectively.

## DISCUSSION

The main finding of this study was that endurance performance (40km TT) improved more in the group of cyclists who showed a continuous increase in HRR during the 4 weeks of high intensity training compared to the group of cyclists who had a decrease in HRR towards the end of the HIT period.

### ***Changes in performance parameters***

Improvements in performance parameters in both groups were in accordance with earlier reported improvements after HIT in already well-trained cyclists (Laursen *et al.* 2002; Stepto *et al.* 1999). However, when the improvements in performance of the subjects were compared to a HIT study, which used a similar training protocol with cyclists of the same calibre ( $VO_{2max}$ :  $65.7 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ , relative PPO:  $5.3 \text{ W} \cdot \text{kg}^{-1}$ ), the improvements in  $G_{Decr}$  seemed to be low (Lindsay *et al.* 1996). The improvement of  $HRR_{HIT}$  in  $G_{Incr}$  ( $11 \pm 1$  beats) over the entire training period was comparable to the findings of Buchheit *et al.* (2008). This study reported a non-significant change in HRR of about 16 beats over 60 seconds (from  $60 \pm 12$  beats before training to  $76 \pm 14$  beats after training) which was higher than their pre assumed meaningful difference of 13 beats in already active adolescents after a HIT program. However this was not discussed in the paper (Buchheit *et al.* 2008). Additionally, it is interestingly to note that the variation in HRR and certain performance parameters increased after HIT period, which could indicate that subjects responded differently to the HIT training.

Although significant changes in descriptive parameters were found between  $G_{Incr}$  and  $G_{Decr}$  for age, bodyweight and body fat percentage, these differences are not

expected to impact the relative change in performance parameters.

### ***Relationships between $HRR_{HIT}$ and 40km TT performance parameters***

Relatively weak correlations ( $r = 0.67 - 0.81$ ) were found between the change in  $HRR_{HIT}$  and the change in 40km performance (Figure 4.3). The relationship between  $HRR_{HIT}$  and the relative performance parameters was slightly better than when compared to absolute performance values. We could only find one study which could be used as a source of comparison (Buchheit *et al.* 2008). This study showed a comparable relationship ( $r = 0.62$ ) between absolute change in a performance parameters (repeated sprint time) and a change in a 60 second HRR indices.

### ***Change in performance parameters in $G_{Incr}$ and $G_{Decr}$***

There were no differences in performance parameters between  $G_{Incr}$  and  $G_{Decr}$  when the data were expressed in absolute units. However, when these data were expressed in relative values, mean 40km TT power (W) and relative 40km TT power improved significantly more in  $G_{Incr}$  when compared to  $G_{Decr}$ . These improvements in 40km TT time (s) only showed a strong tendency ( $P = 0.058$ ) to have improved more in  $G_{Incr}$  than in  $G_{Decr}$ . Effect size statistics of 40km TT time (1.13) showed a “moderate” to almost “large” chance that the difference found was clinically meaningful. This interpretation is supported by three other studies showing that performance changes of 0.7 - 1.0% in well-trained and elite cyclists should be regarded as meaningful (Currell and Jeukendrup 2008; Lamberts *et al.* 2009b; Paton and Hopkins 2006). The mean difference of 40km TT time between  $G_{Incr}$  and  $G_{Decr}$  was 1.3%.

A possible explanation for the blunted improvement in endurance performance in  $G_{Decr}$ , could be that the training load after the 6<sup>th</sup> HIT session became intolerable and fatigue started to accumulate. This is supported by two independent studies. Halson *et al.* (2002) reported a significant decline in PPO and TT performance after a 2 week period of intensified training (8 HIT sessions), in conjunction with a 29% increase in global mood disturbances and significant higher DALDA score during the intensified training period. Urhausen *et al.* (1998) in contrast reported no change peak performance parameters (10 second and 30 second sprint power and maximal peak power) but a 27% decrease in a time-to-exhaustion test (riding at 83% of  $VO_{2max}$ ) in a group of overtrained endurance athletes (cyclists and triathletes). These findings are

in accordance with our study, which shows an initial impairment in endurance performance rather than in peak performance parameters.

A paradoxical finding however was that the young and better trained cyclists generally struggled to accommodate the training load, in contrast to the slightly less trained cyclists who were able to cope. The explanation is not immediately clear. One possibility could be that the subjects in  $G_{Decr}$  did more training than was prescribed. This however is speculative and will have to be verified in future studies.

Overall, our data suggest that a decrease in  $HRR_{HIT}$  is initially associated with a decrease in endurance cycling capacity rather than in peak power performance parameters and possibly reflects the accumulation of fatigue. This has interesting implications for monitoring cycling performance as it suggests that changes in endurance cycling performance can possibly be monitored by changes in HRR in contrast to peak power performance.

### ***Limiting factors of the study and future research***

Although the predetermined sample size requirement was met, future studies should attempt to increase the sample size to strengthen the statistical power.

Based on the curvilinear relationship between training status and improving performance (Foster *et al.* 1996), it can be expected that better cyclists are able to improve less than less trained cyclist after a similar training program. It can therefore be argued that  $G_{Decr}$ , who had a relatively higher relative power, improved less than  $G_{Incr}$  based on a better training status. However, when the change in performance parameters were calculated as relative values, which partly corrects for these differences, significant differences were maintained.

Future research should focus on comparing groups that are fully matched based on general characteristics and physiological parameters. In addition, subjective measurements of symptoms of fatigue, such as RPE (Borg 1982), POMS (McNair *et al.* 1971) and the DALDA (Rushall 1990) scores, should be included in the study design to confirm the development of fatigue and its relationship with changes in HRR.

In conclusion, this study shows that a decrease in HRR during a HIT training period is possibly a consequence of an imbalance between training load and recovery is associated with a blunted improvement in endurance performance, while peak performance is initially unaffected. Therefore the measurement of HRR has the potential to be a useful tool for monitoring fatigue and prescribing training load in well-trained and elite cyclists.

### **PERSPECTIVES**

Improvements in training status are associated with changes in HRR and HRV indices after exercise (Borresen and Lambert 2007; Buchheit *et al.* 2008; Lamberts *et al.* 2009a; Sugawara *et al.* 2001; Yamamoto *et al.* 2001). Although it is widely accepted that these changes are associated with lower health risks (Cole *et al.* 1999), it is not known if they can also be used to monitoring changes in the training status in well-trained athletes. Buchheit (2007b; 2008) recently reported that changes in HRR indices are mainly associated with recently applied training loads, while changes in HRV indices are mainly associated with a long term modulation of the autonomic nervous system.

The outcomes of this study supports this hypothesis as it shows that HRR indeed responds to a recently applied training load. In addition, we showed that a decrease in HRR is associated with a blunted improvement in endurance performance. This suggests that a decrease in HRR can possibly predict an inability to cope with the training load and the accumulation of fatigue. Therefore the measurement of HRR after a standardised warm-up (Lamberts *et al.* 2009b), has the potential to have an important role in monitoring cycling performance and optimizing training programs.

### **ACKNOWLEDGEMENTS**

The authors would like to thank all cyclists who participated in this study. This study was funded by the van Ewijck foundation and the Medical Research Council of South Africa, Discovery Health and the University of Cape Town.

## REFERENCES

- Altman DG (1991) Practical Statistics for Medical Research. Chapman and Hall, London, UK.
- American College of Sports Medicine (2007) Submaximal Exercise Tests. In: Whaley MH, Brubaker PH and Otto RM. (eds) ACSM's Guidelines for Exercise Testing and Prescription. Baltimore, MD, USA Lippincott Williams & Wilkins, pp 70-74.
- Borg GA (1982) Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 14: 377-381
- Borresen J and Lambert MI (2007) Changes in heart rate recovery in response to acute changes in training load. *Eur J Appl Physiol* 101: 503-511
- Borresen J and Lambert MI (2008) Autonomic control of heart rate during and after exercise - measurements and implications for monitoring training status. *Sports Med* 28: 633-646
- Buchheit M, Laursen PB and Ahmaidi S (2007a) Parasympathetic reactivation after repeated sprint exercise. *Am J Physiol Heart Circ Physiol* 293: H133-H141
- Buchheit M, Millet GP, Parisy A, Pourchez S, Laursen PB and Ahmaidi S (2008) Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Med Sci Sports Exerc* 40: 362-371
- Buchheit M, Papelier Y, Laursen PB and Ahmaidi S (2007b) Noninvasive assessment of cardiac parasympathetic function: postexercise heart rate recovery or heart rate variability? *Am J Physiol Heart Circ Physiol* 293: H8-H10



- Cole CR, Blackstone EH, Pashkow FJ, Snader CE and Lauer MS (1999) Heart-rate recovery immediately after exercise as a predictor of mortality. *N Engl J Med* 341: 1351-1357
- Currell K and Jeukendrup AE (2008) Validity, reliability and sensitivity of measures of sporting performance. *Sports Med* 38: 297-316
- Durnin JVGA and Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr* 32: 77-97
- Foster CF, Daines E, Hector L, Snyder AC and Welsh R (1996) Athletic performance in relation to training load. *Wis Med J* 95: 370-374
- Gnehm P, Reichenbach S, Altpeter E, Widmer H and Hoppeler H (1997) Influence of different racing positions on metabolic cost in elite cyclists. *Med Sci Sports Exerc* 29: 818-823
- Halsen SL, Bridge MW, Meeusen R, Busschaert B, Gleeson M, Jones DA and Jeukendrup AE (2002) Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* 93: 947-956
- Hawley JA and Noakes TD (1992) Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur J Appl Physiol Occup Physiol* 65: 79-83
- Jeukendrup A (2002) High-performance cycling. Human Kinetics Publishers, Inc., Champaign, IL, USA.
- Kaikkonen P, Rusko H and Martinmaki K (2008) Post-exercise heart rate variability of endurance athletes after different high-intensity exercise interventions.

Scand J Med Sci Sports 18: 511-519

Kenttä G and Hassmén P (1998) Overtraining and recovery. A conceptual model. Sports Med 26: 1-16

Kiviniemi AM, Hautala AJ, Kinnunen H and Tulppo MP (2007) Endurance training guided individually by daily heart rate variability measurements. Eur J Appl Physiol 101: 743-751

Lambert MI and Borresen J (2006) A theoretical basis of monitoring fatigue: a practical approach for coaches. International Journal of Sports Science & Coaching 1: 371-388

Lamberts RP, Lemmink KA, Durandt JJ and Lambert MI (2004) Variation in heart rate during submaximal exercise: implications for monitoring training. J Strength Cond Res 18: 641-645

Lamberts RP, Swart J, Noakes TD and Lambert MI (2009a) Changes in heart rate recovery after high-intensity training in well-trained cyclists. Eur J Appl Physiol 105: 705-713

Lamberts RP, Swart J, Woolrich RW, Noakes TD and Lambert MI (2009b) Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status. International SportMed Journal 10: 33-44

Laursen PB, Blanchard MA and Jenkins DG (2002) Acute high-intensity interval training improves  $T_{vent}$  and peak power output in highly trained males. Can J Appl Physiol 27: 336-348

Lindsay FH, Hawley JA, Myburgh KH, Schomer HH, Noakes TD and Dennis SC (1996) Improved athletic performance in highly trained cyclists after

interval training. *Med Sci Sports Exerc* 28: 1427-1434

Lucia A, Hoyos J, Santalla A, Perez M and Chicharro JL (2002a) Kinetics of  $\text{VO}_2$  in professional cyclists. *Med Sci Sports Exerc* 34: 320-325

Lucia A, Rivero JL, Perez M, Serrano AL, Calbet JA, Santalla A and Chicharro JL (2002b) Determinants of  $\text{VO}_2$  kinetics at high power outputs during a ramp exercise protocol. *Med Sci Sports Exerc* 34: 326-331

McNair DM, Lorr M and Droppleman LF (1971) Manual for the Profile of Mood Status. Educational and Industrial Testing Service, San Diego, CA.

Meeusen R, Duclos M, Gleeson M, Rietjens GJ, Steinacker JM and Urhausen A (2006) Prevention, diagnosis and treatment of the overtraining syndrome. *European Journal of Sports Science* 6: 1-14

Mujika I and Padilla S (2001) Physiological and performance characteristics of male professional road cyclists. *Sports Med* 31: 479-487

Padilla S, Mujika I, Orbananos J and Angulo F (2000) Exercise intensity during competition time trials in professional road cycling. *Med Sci Sports Exerc* 32: 850-856

Palmer GS, Dennis SC, Noakes TD and Hawley JA (1996) Assessment of the reproducibility of performance testing on an air-braked cycle ergometer. *Int J Sports Med* 17: 293-298

Paton CD and Hopkins WG (2006) Ergometer error and biological variation in power output in a performance test with three cycle ergometers. *Int J Sports Med* 27: 444-447

Ross WD and Marfell-Jones MJ (1991) Kinanthropometry. In: MacDougall JD,

Wenger HA and Green HS. (eds) *Physiological Testing of the High Performance Athlete*. Champaign, IL: Human Kinetics, pp 223-308.

Rushall BS (1990) A Tool for Measuring Stress Tolerance in Elite Athletes. *Journal of Applied Sport Psychology* 2: 51-66

Shepley B, MacDougall JD, Cipriano N, Sutton JR, Tarnopolsky MA and Coates G (1992) Physiological effects of tapering in highly trained athletes. *J Appl Physiol* 72: 706-711

Solberg G, Robstad B, Skjønberg OH and Borchsenius F (2005) Respiratory gas exchange indices for estimating the anaerobic threshold. *J Sports Sci Med* 4: 29-36

Stephens NK, Hawley JA, Dennis SC and Hopkins WG (1999) Effects of different interval-training programs on cycling time-trial performance. *Med Sci Sports Exerc* 31: 736-741

Sugawara J, Murakami H, Maeda S, Kuno S and Matsuda M (2001) Change in post-exercise vagal reactivation with exercise training and detraining in young men. *Eur J Appl Physiol* 85: 259-263

Urhausen A, Gabriel HH, Weiler B and Kindermann W (1998) Ergometric and psychological findings during overtraining: a long-term follow-up study in endurance athletes. *Int J Sports Med* 19: 114-120

Yamamoto K, Miyachi M, Saitoh T, Yoshioka A and Onodera S (2001) Effects of endurance training on resting and post-exercise cardiac autonomic control. *Med Sci Sports Exerc* 33: 1496-1502

World Medical Association Declaration of Helsinki (2002); Ethical principles for medical research involving human subjects. *Nurs Ethics* 9: 105-10

University of Cape Town

# Chapter 5

***Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status \****

\* **R.P. Lamberts**, J. Swart, R. Woolrich, T.D. Noakes and M.I. Lambert. Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status. *International SportsMed Journal* 10(1): 33-44, 2009

## ABSTRACT

Small changes in performance, as low as 1%, are regarded as meaningful in well-trained cyclists. Being able to detect these changes is necessary to fine tune training and optimise performance. The typical error of measurement (TEM) in common performance cycle tests is about 2 - 3%. It is not known whether this TEM is lower in well-trained cyclists and therefore whether small changes in performance parameters are detectable. In this research, after familiarisation, 17 well-trained cyclists each completed three Peak Power Output (PPO) tests (including  $VO_{2max}$ ) and three 40km time trials (40km TT). All tests were performed after a standardised warm-up at the same relative intensity and under a strict testing-protocol. TEM within the PPO-test was 2.2% for  $VO_{2max}$  and 0.9% for PPO, while TEM for the 40km TT was 0.9%. In conclusion, measurement of PPO and 40km TT time, after a standardised warm-up, has sufficient precision in well-trained cyclists to detect small meaningful changes.

### Keywords:

High-performance • cycling • precision • testing • monitoring • meaningful differences.

## INTRODUCTION

In elite professional cycling small differences in performance can determine the difference between finishing in the main bunch and winning the race. Three extreme examples are the Tour de France of 1968 (Jan Jansen), 1989 (Greg Lemond) and 2007 (Alberto Contador), where all Tours were won by marginal overall differences, 38 seconds (0.07%), 8 seconds (0.003%) and 23 seconds (0.08%) respectively. However, more generally, performance changes of 1.0% in well-trained and elite cyclists are regarded as meaningful (Currell and Jeukendrup 2008; Paton and Hopkins 2006). Therefore in well-trained and elite cyclists, any within subject tests of cycling performance should have sufficient precision to detect changes of this magnitude.

Performance tests that are frequently used to predict cycling talent and monitor changes in training status are a 40km time trial (40km TT) and a peak power output (PPO) test, either with or without respiratory gas analysis ( $\text{VO}_{2\text{max}}$ ) (Hawley and Noakes 1992; Jeukendrup 2002; Jeukendrup *et al.* 2000; Lucia *et al.* 2000; Lucia *et al.* 2002; Lucia *et al.* 2004; Mujika and Padilla 2001; Padilla *et al.* 2000). The typical error of the measurement (TEM) of these tests, when used in a population of general cyclists, has been recorded as high as 2% to 3% (Paton and Hopkins 2001). There are, however, limited studies which have focused on the repeatability of these measurements in well-trained cyclists (Balmer *et al.* 2000; Palmer *et al.* 1996; Smith *et al.* 2001). Most these studies were conducted on Kingcycle ergometers which have a relatively large measurement error (Paton and Hopkins 2006). This lack of precision makes it difficult to measure meaningful differences in performance in well-trained and elite cyclists.

The typical error of measurement (TEM) in performance consists of a systematic error and a random error. The systematic error relates to the inability of a measurement tool (ergometer) to accurately measure the performance parameter (for example, power output). With the recent development of more accurate ergometers, such as the Powertap (Bertucci *et al.* 2005; Paton and Hopkins 2006), SRM (Balmer *et al.* 2004; Paton and Hopkins 2006) and Computrainer<sup>TM</sup> (Davidson *et al.* 2007), the systematic error is reduced. The random error describes the measurement error



within a repeated test scenario and occurs as a result of ergometer measurement variation (for example, caused by the calibration procedure) and a biological test-retest variation in cyclists who do not always perform each test at the same identical (sub)-maximal effort (Paton and Hopkins 2001). Since well-trained cyclists are more experienced, a lower test-retest variation might be expected. Accordingly, the TEM in performance testing in these cyclists might be substantially lower.

However, whether this is low enough to detect meaningful differences in performance (i.e. 1.0%) (Currell and Jeukendrup 2008; Paton and Hopkins 2006) is not known. Therefore the aim of this study was to determine the TEM of different laboratory tests for the prediction of performance, including the peak power output test and the 40km time trial, within a group of well-trained cyclists who maintained a constant training status. To these authors' knowledge, no study has specifically determined the TEM and day-to-day variation of performance testing of well-trained cyclists on the Computrainer<sup>TM</sup> ergometer.

## METHODS

### *Recruitment*

Seventeen well-trained, competitive, male, road-racing cyclists, between the ages of 18 and 40 years, were recruited for the study. All cyclists were engaged in pre-season base training at the time of the study. Inclusion criteria for the study were a minimum of 6 training hours per week over the 6 week period before the trial and a minimum competitive cycling background of at least 3 years. Prior to participation all cyclists were informed of the risks and stresses associated with the research protocol, were personally interviewed about their training history and competitive participation level, completed a Physical Activity Readiness Questionnaire (PAR-Q) (American College of Sports Medicine 2007) and signed an informed consent form. The study was approved by the Ethics and Research Committee of the Faculty of Health Sciences of the University of Cape Town, and the principles of the World Medical Association Declaration of Helsinki and the ACSM Guidelines for Use of Human Subjects were adopted in this study.

**Study design**

The study was conducted over 5 consecutive weeks during which each subject completed four peak power output tests (including respiratory gas analysis) and four 40km time trial tests. The 40km time trial tests were performed 72 hours after the peak power output tests and 96 hours before the following week's peak power output test in order to avoid the influence of fatigue on the test outcomes. Subjects were allowed to postpone both tests once during the 5-week period. Valid reasons for postponement included not feeling physically well (e.g. sore throat, coughing), not being able to start the testing at the required time due to unforeseen events (e.g. traffic holdups, power cuts) or inadequate sleep prior to the test.

The first week of testing was used to familiarise the cyclists to the different testing protocols and to establish the correct intensity of the warm-up protocol (see warm-up protocol). In the following four weeks all subjects repeated the same protocol on three separate occasions. Each of the three peak power output (PPO) and 40km time trial (40km TT) tests were scheduled at the same time of day (within 1 hour) and were performed under controlled and stable climatic conditions. Subjects were asked to refrain from eating for 2 hours before the test and from drinking any caffeine prior to 3 hours before the test. The same cycling outfit was worn throughout the testing period and no changes in the bike set-up were allowed.

Before each test cyclists were questioned about 'sport injuries', 'sleeping patterns', 'use of medication', 'caffeine use', 'general fatigue' and 'muscle soreness'. If 'general fatigue' and/or 'muscle soreness' were present, the cyclist was asked to rate his perception of pain on a continuous scale ranging from 0 to 10, where 0 = 'nothing at all' and 10 = 'maximal'. A questionnaire also checked whether the 'same bike' was used, whether changes were made in the 'bike set-up' and whether the cyclists were wearing the 'same cycling outfit'. During the testing period the cyclists were asked to maintain the same training regime and not to increase their training volume or intensity shortly before or during the trial. This was done in order to maintain the same training status of the cyclists throughout the testing period.

### ***Preliminary testing***

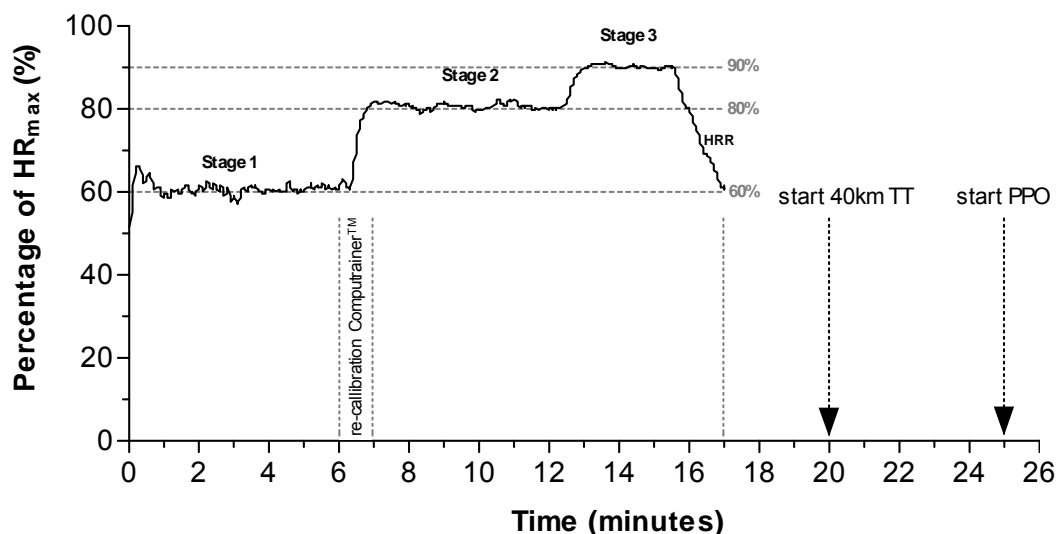
Anthropometric measurements, including height, weight and seven skinfolds (triceps, biceps, supra-iliac, sub-scapular, calf, thigh and abdomen) (Ross and Marfell-Jones 1991), were performed at the start of the study, and body fat was determined as the sum of seven skinfolds and also as a percentage of body mass (Durnin and Womersley 1974).

### ***Calibration protocol***

Before each testing and training session cyclists were weighed to check for any significant changes in body mass which might reflect plasma volume changes. The rear wheel tyre of the subject's own bicycle was inflated to 800 kPa and the bicycle was mounted, by a rear axle quick release mechanism, to an electronically braked cycle ergometer (Computrainer<sup>TM</sup> Pro 3D, RacerMate, Seattle, USA). Before the start of a standardised warm-up protocol the contact pressure of the load-generator against the rear wheel was calibrated to 0.88 - 0.93kg. Six minutes into the warm-up protocol, by which time the tyre had warmed-up, the load generator was re-calibrated to 0.88-0.93kg as recommended by Davison *et al.* (2007).

### ***Warm-up protocol***

To standardise the duration and intensity of the warm up a specially designed warm-up protocol (also known as the Lamberts and Lambert Submaximal Cycle Test (LSCT)) was used. This 17-minute protocol was performed on a simulated flat course, with three different exercise intensities defined by different target heart rates (Figure 5.1). During the test cyclists had to elicit and maintain their heart rate ( $\pm 1$  beats $\cdot$ min<sup>-1</sup>) corresponding to 60%, 80% and 90% of their maximum heart rate (HR<sub>max</sub>) during each of the three stages. The subjects either cycled faster or slower to correct their heart rate when this deviated by at least 2 beats $\cdot$ min<sup>-1</sup>. The maximum heart rate of each subject, which was measured during the familiarization peak power output test, was used to calculate target heart rates for the warm-up. The target heart rates for the initial warm-up before the familiarisation Peak Power output test were based on a predicted HR<sub>max</sub> (220 – age).



**Figure 5.1** An arbitrary heart rate response (—) expressed a percentage of  $HR_{max}$  during the warm-up protocol (LSCT). The time frames up to the start of the peak power output tests (PPO) and the 40km time trial (40km TT) are also indicated.

After the initial calibration of the Computrainer™ system and the first stage of the test, which involved cycling for 6 minutes at 60% of  $HR_{max}$ , a second 30 seconds period was used to recalibrate the Computrainer™ system (Davison *et al.* 2007). The second stage, also of 6 minutes, was performed at 80% of  $HR_{max}$ . The third and last stage, which followed directly after the second stage and lasted 3 minutes, was performed at 90% of  $HR_{max}$ . After completing the test subjects are asked to stop cycling, sit straight up, and to recover for 90 seconds. Apart from standardising the warm-up to the same relative intensity, the LSCT was also designed to collect data, such as power output, perception of effort and heart rate recovery under controlled submaximal conditions, which potentially could assist in predicting and monitoring performance in future studies.

### **Peak power output test**

The Peak Power Output test (PPO), which included respiratory gas analysis ( $VO_{2max}$ ), was started exactly 3 minutes after the end of the warm-up. The PPO test was performed at a starting work rate of  $2.50 \text{ W} \cdot \text{kg}^{-1}$  body mass after which the load was increased incrementally by 20 W each minute until the cyclist could not sustain a cadence greater than 70 rpm or was volitionally exhausted. During the progressive exercise test to exhaustion, ventilation volume ( $V_E$ ), oxygen uptake ( $VO_2$ ) and  $CO_2$

production ( $\text{VCO}_2$ ) were measured over 15 second intervals using an online breath-by-breath gas analyser and pneumotach (Oxycon, Viasis, Hoechberg, Germany). Subjects were verbally encouraged to perform to maximal exhaustion. Peak power output was determined as the mean power output during the final minute of the PPO test where as  $\text{VO}_{2\text{max}}$  ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) was determined as the highest recorded reading for 30 seconds.

### **40km time trial**

The 40km time trial (40km TT) tests were performed on a simulated 40km flat time trial course which was created on the Computrainer<sup>TM</sup> system. All cyclists were asked to complete the 40km distance in the fastest possible time and were allowed to drink water ad libitum during the trial. In an attempt to control for any pacing strategies, the subjects were only given their completed distance and were not given any feedback about other aspects of their performance, such as power output, time or speed. No verbal encouragement was given during the time trial, except for the last kilometre when the distance was counted down in 100 m sections and during the last hundred meters in 10m sections. About 30 minute after finishing the time trial each cyclist gave an overall rating of perceived exertion for the 40km TT (6-20 Borg-scale) (Davison *et al.* 2007).

### **Data collection and analysis**

Power output, speed, cadence and elapsed time were measured during all trials and stored by the Computrainer<sup>TM</sup> software at a rate of 34 Hz. Heart rate data during these tests were captured with Suunto T6 heart rate monitors (Suunto Oy, Vantaa, Finland) and stored every 2 seconds. Oxygen uptake ( $\text{VO}_2$ ) and  $\text{CO}_2$  production ( $\text{VCO}_2$ ) were measured with an online breath-by-breath gas analyser and pneumotach (Oxycon, Viasis, Hoechberg, Germany) and stored as average values over 8 breaths.

Due to the slow half-life of heart rate (Achten and Jeukendrup 2003) and subjects making fine adjustments to their work load to reach specific heart rates during the warm-up, the heart rate and performance data in the first minute of each stage were excluded from analysis. Therefore average performance and heart rate values were calculated over a five minute period (from minute 1.0 to 6.0 and from 7.5 to 12.5) for

stage 1 and 2 respectively, and for a two minute period (13.5-15.5) for stage 3. Performance and heart rate data from the PPO test and the 40km TT test were analysed for the full period of the data capture.

Analysis of performance data was performed using CyclingPeaks™ analysis software (WKO+ edition, Version 2.1, 2006, Lafayette, CO, USA) and the Computrainer™ coaching software (Version 1.5.308, RacerMate, Seattle, USA). Heart rate data were analysed with Suunto Training Manager (Version 2.1.0.3, Suunto Oy, Vantaa, Finland).

### Statistical analysis

The data were analysed with STATISTICA version 8.0 (Stat-soft Inc., Tulsa, OK, USA) for any statistical significance ( $P < 0.05$ ). All data are expressed as means  $\pm$  standard deviation ( $\bar{X} \pm s$ ). The mean time and the physiological responses during three submaximal cycle tests,  $\text{VO}_{2\text{max}}$  tests and three 40km time trials were compared by using a repeated measures analysis of variance ANOVA. Reliability for each variable was also assessed by calculating interclass correlation coefficient (ICC) and the 95% confidence intervals (Vincent 1995). Typical error of the measurement (TEM) and typical error of the measurement as a percentage (%), expressed as a % of the mean score, were calculated with 90% confidence intervals, using a spreadsheet downloaded from <http://www.newstats.org>. (Bland and Altman 1986)

## RESULTS

Seventeen cyclists were recruited for this study; however, the data set of 2 cyclists were excluded from analysis because one had not completed the trial and one subject had used a potentially performance enhancing drug (methylphenidate (Ritalin)) during the trial. This drug was prescribed by a general practitioner and the subject was unaware of the possible performance enhancing effects of this drug (Swart *et al.* 2008). The general characteristics and performance parameters of the remaining 15 cyclists are shown in Table 5.1.

**Table 5.1** General characteristics of cyclists (n = 15)

Variable	$\bar{X} \pm s$
Age (years)	31 $\pm$ 4
Body mass (kg)	78.6 $\pm$ 8.3
Stature (m)	1.82 $\pm$ 0.08
Percentage body fat (%)	16.3 $\pm$ 3.6
Skinfolds (mm)	70.1 $\pm$ 26.6
Training time before the trial (h·wk <sup>-1</sup> )	10 $\pm$ 3
Competitive cycling experience (years)	7 $\pm$ 3
Cape Argus Pick 'n Pay Cycle Tour race time (min.s)*	177.16 $\pm$ 9.22
PPO (W)	382 $\pm$ 48
PPO (W·kg <sup>-1</sup> )	4.87 $\pm$ 0.51
VO <sub>2max</sub> (ml·kg <sup>-1</sup> ·min <sup>-1</sup> )	56.91 $\pm$ 6.77
40km TT (min.s)	66.11 $\pm$ 3.39

\* Cape Argus Pick 'n Pay Cycle Tour, 109 km road cycle race

Nine cyclists completed the testing period within 4 weeks, while six riders postponed, for legitimate reasons, one testing session, which resulted in a 5-week testing period for these cyclists. The questionnaire which each cyclist completed before each test revealed that none had consumed caffeine within the 3 hours before the test, and all subjects had maintained their same dietary pattern. Furthermore, the questionnaire confirmed that all cyclists had slept well the night before each test, none reported any symptoms of general fatigue or muscle soreness, all were wearing the same cycling outfits and none made any changes to their bicycle set-up.

All testing was performed on the same day and time of the week (within 1 hour) and under stable climatic conditions (21.7  $\pm$  0.7 °C, 52  $\pm$  4% relative humidity, 101.8  $\pm$  0.7 kPa). The body mass of the cyclists remained stable within 1.0  $\pm$  0.4% (0.8  $\pm$  0.3 kg) throughout the study.

### ***Warm-up protocol***

Subjects were able to closely regulate their heart rate by adjusting their exercise intensity during the 3 different stages of the warm-up protocol. The mean change in heart rate at 60% of HR<sub>max</sub> was 0  $\pm$  1 beats (range, -3 to 2 beats), at 80% of HR<sub>max</sub>

was  $0 \pm 1$  beats (range, -1 to 2 beats) and at 90% of  $HR_{max}$  was  $0 \pm 1$  beats (range, -1 to 1 beat). When the intensity of the different stages of the warm-up are expressed as a percentage of peak power output, stage 1, 2 and 3 were equal to  $31 \pm 5\%$ ,  $60 \pm 4\%$  and  $80 \pm 3\%$  of PPO.

**Table 5.2** Mean physiological changes during the warm-up protocol (LSCT). The data are expressed as  $X \pm s$  and the ICC (95% CI) ( $n = 15$ )

	LSCT 1	LSCT 2	LSCT 3	LSCT 4	LSCT 5	LSCT 6	Mean	ICC
<b>Stage 1 (cycling at 60% of <math>HR_{max}</math>)</b>								
Average power (W)	$114 \pm 24$	$114 \pm 23$	$124 \pm 28$	$111 \pm 22$	$119 \pm 26$	$118 \pm 22$	$117 \pm 21$	<b>0.91</b> (0.83 – 0.96)
Average power (%)	$30 \pm 5$	$30 \pm 5$	$33 \pm 7$	$29 \pm 5$	$32 \pm 7$	$32 \pm 7$	$31 \pm 5$	<b>0.90</b> (0.81 – 0.91)
Average HR (beats·min <sup>-1</sup> )*	$114 \pm 4$	$114 \pm 4$	$113 \pm 4$	$114 \pm 3$	$114 \pm 4$	$114 \pm 4$	$114 \pm 4$	<b>0.99</b> (0.98 – 1.00)
Average HR (%)**	$60 \pm 1$	$60 \pm 1$	$59 \pm 1$	$60 \pm 1$	$60 \pm 1$	$60 \pm 1$	$60 \pm 1$	<b>0.87</b> (0.76 – 0.95)
RPE (units)	$8 \pm 1$	$8 \pm 1$	$8 \pm 1$	$8 \pm 1$	$8 \pm 1$	$8 \pm 1$	$8 \pm 1$	<b>0.88</b> (0.78 – 0.95)
<b>Stage 2 (cycling at 80% of <math>HR_{max}</math>)</b>								
Average power (W)	$231 \pm 33$	$230 \pm 32$	$239 \pm 31$	$224 \pm 27$	$225 \pm 29$	$230 \pm 29$	$230 \pm 29$	<b>0.98</b> (0.96 – 0.99)
Average power (%)	$61 \pm 5$	$61 \pm 5$	$63 \pm 5$	$59 \pm 4$	$59 \pm 5$	$61 \pm 4$	$60 \pm 4$	<b>0.94</b> (0.88 – 0.98)
Average HR (beats·min <sup>-1</sup> )*	$152 \pm 5$	$152 \pm 5$	$152 \pm 5$	$152 \pm 5$	$153 \pm 5$	$153 \pm 5$	$152 \pm 5$	<b>0.99</b> (0.98 – 1.00)
Average HR (%)**	$80 \pm 1$	$80 \pm 1$	$80 \pm 1$	$80 \pm 1$	$80 \pm 1$	$80 \pm 1$	$80 \pm 1$	<b>0.86</b> (0.74 – 0.94)
RPE (units)	$12 \pm 1$	$13 \pm 1$	$13 \pm 1$	$12 \pm 1$	$12 \pm 1$	$13 \pm 1$	$12 \pm 1$	<b>0.85</b> (0.73 – 0.94)
<b>Stage 3 (cycling at 90% of <math>HR_{max}</math>)</b>								
Average power (W)	$304 \pm 41$	$304 \pm 40$	$306 \pm 40$	$303 \pm 41$	$303 \pm 38$	$305 \pm 40$	$304 \pm 40$	<b>1.00</b> (0.99 – 1.00)
Average power (%)	$80 \pm 4$	$80 \pm 3$	$80 \pm 4$	$79 \pm 4$	$79 \pm 3$	$80 \pm 3$	$80 \pm 3$	<b>0.98</b> (0.96 – 0.99)
Average HR (beats·min <sup>-1</sup> )*	$172 \pm 5$	$171 \pm 5$	$171 \pm 5$	$171 \pm 6$	$172 \pm 5$	$171 \pm 5$	$171 \pm 5$	<b>0.99</b> (0.98 – 1.00)
Average HR (%)**	$90 \pm 1$	$90 \pm 1$	$90 \pm 0$	$90 \pm 1$	$90 \pm 0$	$90 \pm 1$	$90 \pm 1$	<b>0.86</b> (0.74 – 0.94)
RPE (units)	$16 \pm 1$	$16 \pm 1$	$16 \pm 1$	$16 \pm 1$	$16 \pm 1$	$16 \pm 1$	$16 \pm 1$	<b>0.86</b> (0.74 – 0.94)

\* average heart rate over the last 5 minutes \*\* average heart rate over the last 2 minutes

The mean physiological responses of the cyclists to the warm-up, expressed as absolute and relative values, are shown in Table 5.2. ICC were also calculated over all 6 warm-up sessions and ranged from  $R = 0.87$  to 1.00 (see also Table 5.2).



The TEM, expressed as absolute and relative (percentage) values (Table 5.3), were calculated over the 3 warming-up sessions that were conducted before the start of the 40km TT. The TEM of the average power output over the 3 stages ranged from 4 - 14 W (1.5 - 12.4%) with a TEM in average heart rate ranging from 1.1 to 0.9 beats (0.5 - 0.9%) (Table 5.3).

**Table 5.3** Parameters describing typical error of measurement within the three warm-up sessions (LSCT) which were performed before the 40km time trials. Data are expressed as typical error of measurement (**TEM**) and typical error of measurement as a CV (%) (**TEM%**) and the 90% CI (n = 15).

Variable		LSCT 2-1 <sup>†</sup>	LSCT 3-2 <sup>#</sup>	LSCT 3-1 <sup>\$</sup>	Mean
<b>Stage 1 (cycling at 60% of HR<sub>max</sub>)</b>					
<b>TEM</b>	Average power (W)	15.4 (11.8 – 22.5)	13.6 (10.5 – 19.8)	12.5 (9.6 – 18.2)	<b>13.9</b> (11.8 – 16.9)
<b>TEM%</b>	Average power (%)	13.7 (10.4 – 20.6)	11.5 (8.7 – 17.2)	11.9 (9.0 – 17.8)	<b>12.4</b> (10.4 – 15.3)
<b>TEM</b>	Average HR (beats·min <sup>-1</sup> )	1.2 (0.9 – 1.8)	1.0 (0.77 – 1.5)	1.0 (0.76 – 1.4)	<b>1.1</b> (0.9 – 1.4)
<b>TEM%</b>	Average HR (%)	1.1 (0.8 – 1.6)	0.9 (0.7 – 1.3)	0.9 (0.7 – 1.3)	<b>0.9</b> (0.8 – 1.2)
<b>Stage 2 (cycling at 80% of HR<sub>max</sub>)</b>					
<b>TEM</b>	Average power (W)	8.2 (6.3 – 12.0)	9.8 (7.6 – 14.4)	7.2 (5.5 – 10.4)	<b>8.5</b> (7.2 – 10.3)
<b>TEM%</b>	Average power (%)	3.8 (2.9 – 5.6)	4.5 (3.4 – 6.6)	3.1 (2.4 – 4.5)	<b>3.8</b> (3.2 – 4.7)
<b>TEM</b>	Average HR (beats·min <sup>-1</sup> )	1.1 (0.8 – 1.5)	0.8 (0.6 – 1.1)	1.1 (0.8 – 1.6)	<b>1.0</b> (0.8 – 1.2)
<b>TEM%</b>	Average HR (%)	0.7 (0.5 – 1.0)	0.5 (0.4 – 0.7)	0.7 (0.5 – 1.0)	<b>0.6</b> (0.6 – 0.8)
<b>Stage 3 (cycling at 90% of HR<sub>max</sub>)</b>					
<b>TEM</b>	Average power (W)	3.2 (2.5 – 4.7)	5.2 (4.0 – 7.6)	4.6 (3.5 – 6.7)	<b>4.4</b> (3.7 – 5.4)
<b>TEM%</b>	Average power (%)	1.0 (0.8 – 1.5)	1.8 (1.4 – 2.6)	1.7 (1.3 – 2.5)	<b>1.5</b> (1.3 – 1.9)
<b>TEM</b>	Average HR (beats·min <sup>-1</sup> )	0.7 (0.6 – 1.1)	0.9 (0.7 – 1.3)	1.1 (0.9 – 1.6)	<b>0.9</b> (0.8 – 1.1)
<b>TEM%</b>	Average HR (%)	0.4 (0.5 – 0.6)	0.5 (0.4 – 0.8)	0.7 (0.5 – 1.0)	<b>0.5</b> (0.5 – 0.7)

<sup>†</sup> TEM and TEM% between LSCT 2 and LSCT 1, <sup>#</sup> TEM and TEM% between LSCT 3 and LSCT 2, <sup>\$</sup> TEM and TEM% between LSCT 3 and LSCT 1

The average time between the end of the warm-up and the start of the PPO test was 7 minutes and 58 seconds with a standard deviation of 11 seconds. The time between the end of the warm-up and the start of the 40km TT was 3 minutes and 8 seconds with a standard deviation of 9 seconds.

### **Peak power output test and the 40km time trial**

There were no significant changes in any of the performance parameters over the testing period (Table 5.4). Mean physiological responses of the cyclists during the peak power output test and the 40km time trial as well as the ICC are presented in Table 5.4. High ICCs ( $R=0.99 - 1.00$ ) were found for the performance parameters of peak power output, relative peak power output, maximum oxygen uptake ( $VO_{2max}$ ) and time to complete the time trial. The average heart rate during the 40km TT was  $173 \pm 5$  beats·min<sup>-1</sup>, which represents about 92% of heart rate maximum with an ICC of  $R = 0.96$ . Rating of perceived exertion (RPE) for the 40km TT remained fairly constant (16 - 18) with an ICC of  $R = 0.90$ .

**Table 5.4** Mean time and physiological changes during the three Peak Power Output tests and 40km time trials. The data are expressed as  $X \pm s$  and the ICC (95% CI) ( $n = 15$ ).

Variable	Test 1	Test 2	Test 3	ICC
<b>Peak power output test (PPO)</b>				
PPO (W)	$381 \pm 47$	$382 \pm 48$	$382 \pm 49$	<b>1.00</b> (0.99 – 1.00)
PPO (W·kg <sup>-1</sup> )	$4.86 \pm 0.50$	$4.87 \pm 0.53$	$4.87 \pm 0.49$	<b>1.00</b> (0.99 – 1.00)
$VO_{2max}$ (ml·kg <sup>-1</sup> ·min <sup>-1</sup> )	$56.49 \pm 7.13$	$56.71 \pm 6.63$	$57.41 \pm 6.63$	<b>0.99</b> (0.98 – 1.00)
Max. heart rate (beats·min <sup>-1</sup> )	$190 \pm 5$	$190 \pm 7$	$189 \pm 6$	<b>0.97</b> (0.93 – 0.97)
<b>40km time trial test (40km TT)</b>				
Time (s)	$3980 \pm 229$	$3964 \pm 215$	$3967 \pm 215$	<b>0.99</b> (0.98 – 1.00)
Average HR (beats·min <sup>-1</sup> )	$173 \pm 6$	$174 \pm 5$	$173 \pm 5$	<b>0.96</b> (0.91 – 0.99)
Average HR (%)	$91 \pm 3$	$92 \pm 3$	$91 \pm 3$	<b>0.96</b> (0.91 – 0.99)
Average speed (km·h <sup>-1</sup> )	$36.3 \pm 2.0$	$36.4 \pm 2.0$	$36.4 \pm 1.9$	<b>1.00</b> (0.99 – 1.00)
Average power (W)	$254 \pm 39$	$257 \pm 39$	$256 \pm 38$	<b>1.00</b> (0.99 – 1.00)
Cadence (rpm)	$92 \pm 7$	$91 \pm 8$	$92 \pm 6$	<b>0.93</b> (0.84 – 0.97)
RPE (units)	$17 \pm 1$	$18 \pm 1$	$18 \pm 1$	<b>0.90</b> (0.78 – 0.96)

Differences between all tests (i.e. the second and the first test (test 2-1), the third and the second test (test 3-2) and the third and the first test (test 3-1)) were calculated for the PPO tests and 40km TT tests to determine the typical error of measurement (TEM) of these tests. The TEMs are expressed as absolute and relative values (percentages) and shown in Table 5.5.

**Table 5.5.** Parameters describing typical error of measurement within the three peak power output tests and 40km time trials. Data are expressed as typical error of measurement (**TEM**) and typical error of measurement as a CV (%) (**TEM%**) and the 90% CI (n = 15).

	Variable	Test 2-1 <sup>†</sup>	Test 3-2 <sup>#</sup>	Test 3-1 <sup>§</sup>	Mean
<b>Peak Power Output test</b>					
<b>TEM</b>	VO <sub>2max</sub> (ml·kg <sup>-1</sup> ·min <sup>-1</sup> )	1.2 (0.9 – 1.7)	1.1 (0.9 – 1.6)	1.7 (1.3 – 2.4)	<b>1.3</b> (1.1 – 1.6)
<b>TEM%</b>	VO <sub>2max</sub> (%)	2.0 (1.6 – 3.0)	1.8 (1.4 – 2.6)	2.7 (2.1 – 4.0)	<b>2.2</b> (1.9 – 2.7)
<b>TEM</b>	PPO (W)	2.6 (2.0 – 3.8)	4.2 (3.3 – 6.2)	4.2 (3.3 – 6.2)	<b>3.5</b> (2.9 – 4.5)
<b>TEM%</b>	PPO (%)	0.6 (0.5 – 0.9)	1.1 (0.9 – 1.6)	1.1 (0.8 – 1.6)	<b>0.9</b> (0.8 – 1.2)
<b>TEM</b>	Max. heart rate (beats·min <sup>-1</sup> )	1.8 (1.4 – 2.6)	1.7 (1.3 – 2.4)	1.3 (1.0 – 1.9)	<b>1.6</b> (1.4 – 2.0)
<b>TEM%</b>	Max. heart rate (%)	0.9 (0.7 – 1.4)	0.9 (0.7 – 1.3)	0.7 (0.5 – 1.0)	<b>0.9</b> (0.1 – 1.0)
<b>40km time trial</b>					
<b>TEM</b>	Time (s)	30.7 (23.6 – 44.9)	19.2 (14.7 – 28.0)	29.9 (23.0 – 43.6)	<b>27.1</b> (23.0 – 33.1)
<b>TEM%</b>	Time (%)	0.8 (0.6 – 1.1)	0.5 (0.4 – 0.7)	0.8 (0.6 – 1.1)	<b>0.7</b> (0.6 – 0.8)
<b>TEM</b>	Average power (W)	5.5 (4.2 – 8.0)	2.7 (2.1 – 4.0)	4.5 (3.5 – 6.6)	<b>4.4</b> (3.7 – 5.4)
<b>TEM%</b>	Average power (%)	2.1 (1.6 – 3.1)	1.1 (0.9 – 1.6)	1.8 (1.4 – 2.6)	<b>1.7</b> (1.5 – 2.1)
<b>TEM</b>	Average HR (beats·min <sup>-1</sup> )	1.6 (1.2 – 2.3)	2.1 (1.6 – 3.0)	2.1 (1.6 – 3.1)	<b>1.9</b> (1.6 – 2.4)
<b>TEM%</b>	Average HR (%)	0.9 (0.7 – 1.3)	1.2 (0.9 – 1.8)	1.2 (0.9 – 1.8)	<b>1.1</b> (1.0 – 1.4)
<b>TEM</b>	Average speed (km·h <sup>-1</sup> )	0.3 (0.2 – 0.4)	0.2 (0.1 – 0.3)	0.2 (0.2 – 0.2)	<b>0.23</b> (0.2 – 0.3)
<b>TEM</b>	Cadence (rpm)	3.6 (2.8 – 5.3)	2.6 (2.0 – 3.8)	2.9 (2.2 – 4.5)	<b>3.07</b> (2.6 – 3.8)
<b>TEM</b>	RPE (units)	0.4 (0.3 – 0.6)	0.4 (0.3 – 0.6)	0.6 (0.5 – 0.9)	<b>0.5</b> (0.4 – 0.6)

<sup>†</sup> TEM and TEM% between performance test 2 and performance test 1, <sup>#</sup> TEM and TEM% between performance test 3 and performance test 2, <sup>§</sup> TEM and TEM% between performance test 3 and performance test 1

The mean TEM for peak power during the PPO test was 3.5 W (0.9%) with a mean TEM for VO<sub>2max</sub> of 1.9 ml·kg<sup>-1</sup>·min<sup>-1</sup> (2.2%). Heart rate at the end of the PPO test remained unchanged over the 3 tests and stayed within 2 beats·min<sup>-1</sup>. The mean TEM for time needed for the 40km TT was 27 seconds (0.7%) with mean TEM for average power output during the test of 4.4 W (1.7%). Average heart rate and the rating of perceived exertion during the 40km TT remained relatively unchanged with TEMs of 1.9 beats·min<sup>-1</sup> and 0.5 respectively.

## DISCUSSION

The main finding of this study was that peak power output and 40km TT time had TEMs of 0.9% (3.5 W) and 0.7% (27 seconds) respectively, both which are lower than the magnitude of change (1%) which is regarded as a meaningful difference (Currell and Jeukendrup 2008; Paton and Hopkins 2006). This indicates that both these performance parameters, when measured under well controlled conditions and after a standardised warm-up protocol, have sufficient precision to detect small changes in performance in well-trained and elite cyclists. Interestingly, 40km TT time (0.7%) had a lower TEM than mean power during the 40km TT (1.7%). This difference can be attributed to the units of measurement (Watts or seconds) and suggests that time rather than mean power should be used as an outcome measure for 40km TT performance.

The other marker of performance which was measured in this study ( $\text{VO}_{2\text{max}}$ ) had a slightly higher typical error of measurement of 2.2% ( $1.9 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) which makes this a less sensitive parameter to detect changes in performance over time. This conclusion is supported by the finding of Lucia *et al.* which showed that  $\text{VO}_{2\text{max}}$  improved only by 1.1% ( $0.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) between preseason and in competition period in professional cyclists (Lucia *et al.* 2000). Interestingly, other studies report a wide scatter of  $\text{VO}_{2\text{max}}$  values ( $65.5 - 84.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) in professional cyclists of equal abilities confirming that  $\text{VO}_{2\text{max}}$  alone cannot be an accurate predictor of cycling ability. These three factors; (i) relatively large TEM when determining  $\text{VO}_{2\text{max}}$ , (ii) the small change in  $\text{VO}_{2\text{max}}$  during different phases of a season, and (iii) limited value in discriminating performance differences in cyclists emphasise that  $\text{VO}_{2\text{max}}$  results need to be interpreted with caution in well-trained and elite cyclists. Additional reasoning for this have recently been further discussed by Noakes (2008). The relatively high ICC values in all performance parameters ( $R < 0.95$ ) confirms a good differentiation level between all cyclists, particularly in the context of the fairly homogenous group that was tested (Weir 2005). The reported TEMs in this study are substantially lower than the previously reported in the general population (Hopkins *et al.* 2001; Paton and Hopkins 2001). This difference can probably be attributed to a combination of factors. Firstly, the subjects in this study represented a homogeneous group of well-trained cyclists. This conclusion about the calibre of the cyclists is supported by results of the performance test and the fact that on average the

participants finished within the top 4% (range 0.6% to 8.5%) of the premier local one-day 109 km road racing event in South Africa (Cape Argus Pick 'n Pay Cycle Tour). This race has a total of 1938 climbing meters and was in this year (2007) was won by a Tour de France stage winner in a time of 152 minutes and 32 seconds. Secondly, the warm-up protocol was strictly controlled and of similar relative intensity ( $31 \pm 5\%$ ,  $60 \pm 4\%$  and  $80 \pm 3\%$  of PPO) and duration for each subject. As it is known that different warm-up protocols influence time trial performance (Hajoglou *et al.* 2005), standardisation of the warm-up has probably contributed to greater repeatability. Thirdly, the time between finishing the warm-up and starting the performance test was tightly controlled, while the environmental conditions were kept stable during all tests. Other possible confounding factors which may have influenced the repeatability of the tests, such as feedback of performance parameters during the tests, the use of stimulators or pacers (*e.g.* music), different equipment (*e.g.* clothing and bike) or verbal encouragement were well-controlled according to the suggestions of Curell and Jeukendrup (Currell and Jeukendrup 2008). Large changes in plasma volume, which might have influenced performance-related outcomes (Coyle 2004; Montain *et al.* 1998), did not seem to occur as body mass did not change by more than 1.5% in any of the subjects (Khosla and Billewicz 1964).

The increased capacity to detect small meaningful differences can assist scientists and coaches to more accurately establish the efficacy of training techniques and optimise performance. In addition, the outcomes of this study can possibly explain why certain training techniques, according to elite cyclists and coaches, are highly effective, although scientists could not provide scientific proof to support this conviction.

Without having had the precision of measurement to confirm or refute the beliefs of the elite cyclists and coaches, the role of scientists has in the past always been partly compromised. However, this study shows that by using well-controlled testing protocols, small meaningful differences can be detected, and that science can contribute significantly in the process of further fine tuning training and optimising performance. In addition, the outcomes of this study can also be used for magnitude-based inferences (Batterham and Hopkins 2006) and assist in calculating accurate sample sizes for intervention-type research studies.

In summary, this study has shown that by using a well-controlled, but practical testing protocol, which includes a standardised warm-up at the same relative intensity (LSCT), it is possible to detect small meaningful changes in performance parameters(< 1%) in well-trained cyclists.

### **ACKNOWLEDGEMENTS**

The authors would like to thank all cyclists who participated in this study. This study was funded by the van Ewijck foundation, Medical Research Council of South Africa, Discovery Health and the University of Cape Town Research Unit for Exercise Science and Sports Medicine.

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## REFERENCES

- Achten J and Jeukendrup AE (2003) Heart rate monitoring: applications and limitations. *Sports Med* 33: 517-538
- American College of Sports Medicine (2007) Preparticipation health screening and risk stratification. In: Whaley MH, Brubaker PH and Otto RM. (eds) *ACSM's Guidelines for Exercise Testing and Prescription*. Lippincott Williams & Wilkins, p. 26.
- Balmer J, Bird S, Davison RC, Doherty M and Smith P (2004) Mechanically braked Wingate powers: agreement between SRM, corrected and conventional methods of measurement. *J Sports Sci* 22: 661-667
- Balmer J, Davison RC and Bird SR (2000) Peak power predicts performance power during an outdoor 16.1-km cycling time trial. *Med Sci Sports Exerc* 32: 1485-1490
- Batterham AM and Hopkins WG (2006) Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance* 1: 50-57
- Bertucci W, Duc S, Villerius V and Grappe F (2005) Validity and reliability of the Axiom PowerTrain cycle ergometer when compared with an SRM powermeter. *Int J Sports Med* 26: 59-65
- Bland JM and Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1: 307-310
- Coyle EF (2004) Fluid and fuel intake during exercise. *J Sports Sci* 22: 39-55

- Currell K and Jeukendrup AE (2008) Validity, reliability and sensitivity of measures of sporting performance. *Sports Med* 38: 297-316
- Davidson RCR, Corbett J and Ansley L (2007) Influence of temperature and protocol on the calibration of the computrainer electromagnetically braked cycling ergometer. *J of Sports Sci* 25: 257-258
- Durnin JVGA and Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr* 32: 77-97
- Hajoglou A, Foster C, De Koning JJ, Lucia A, Kernozek TW and Porcari JP (2005) Effect of warm-up on cycle time trial performance. *Med Sci Sports Exerc* 37: 1608-1614
- Hawley JA and Noakes TD (1992) Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur J Appl Physiol Occup Physiol* 65: 79-83
- Hopkins WG, Schabert EJ and Hawley JA (2001) Reliability of power in physical performance tests. *Sports Med* 31: 211-234
- Jeukendrup A (2002) High-performance cycling. Human Kinetics Publishers, Inc., Champaign, IL, USA.
- Jeukendrup AE, Craig NP and Hawley JA (2000) The bioenergetics of World Class Cycling. *J Sci Med Sport* 3: 414-433
- Khosla T and Billewicz WZ (1964) Measurement of change in body-weight. *Br J Nutr* 18: 227-239



- Lucia A, Hoyos J, Perez M and Chicharro JL (2000) Heart rate and performance parameters in elite cyclists: a longitudinal study. *Med Sci Sports Exerc* 32: 1777-1782
- Lucia A, Hoyos J, Perez M, Santalla A, Earnest CP and Chicharro JL (2004) Which laboratory variable is related with time trial performance time in the Tour de France? *Br J Sports Med* 38: 636-640
- Lucia A, Hoyos J, Santalla A, Perez M and Chicharro JL (2002) Kinetics of  $\text{VO}_2$  in professional cyclists. *Med Sci Sports Exerc* 34: 320-325
- Montain SJ, Smith SA, Mattot RP, Zientara GP, Jolesz FA and Sawka MN (1998) Hypohydration effects on skeletal muscle performance and metabolism: a  $^{31}\text{P}$ -MRS study. *J Appl Physiol* 84: 1889-1894
- Mujika I and Padilla S (2001) Physiological and performance characteristics of male professional road cyclists. *Sports Med* 31: 479-487
- Noakes TD (2008) Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *Br J Sports Med* 42: 551-555
- Padilla S, Mujika I, Orbananos J and Angulo F (2000) Exercise intensity during competition time trials in professional road cycling. *Med Sci Sports Exerc* 32: 850-856
- Palmer GS, Dennis SC, Noakes TD and Hawley JA (1996) Assessment of the reproducibility of performance testing on an air-braked cycle ergometer. *Int J Sports Med* 17: 293-298
- Paton CD and Hopkins WG (2001) Tests of cycling performance. *Sports Med* 31: 489-496

- Paton CD and Hopkins WG (2006) Ergometer error and biological variation in power output in a performance test with three cycle ergometers. *Int J Sports Med* 27: 444-447
- Ross WD and Marfell-Jones MJ (1991) Kinanthropometry. In: MacDougall JD, Wenger HA and Green HS. (eds) *Physiological Testing of the High Performance Athlete*. Champaign, IL: Human Kinetics, pp 223-308.
- Smith MF, Davison RC, Balmer J and Bird SR (2001) Reliability of mean power recorded during indoor and outdoor self-paced 40 km cycling time-trials. *Int J Sports Med* 22: 270-274
- Swart J, Lamberts RP, Lambert MI, St Clair Gibson A, Lambert EV, Skowno J and Noakes TD (2008) Exercising with reserve: Evidence that the CNS regulates prolonged exercise performance. *Br J Sports Med* (Epub; ahead of publ.)
- Vincent WJ (1995) *Statistics in Kinesiology*. Human Kinetics Publishers, Inc., Champaign, IL, USA.
- Weir JP (2005) Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res* 19: 231-240

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# Chapter 6

***A novel submaximal cycle test to monitor fatigue and predict cycling performance.\****

\* **R.P. Lamberts**, J. Swart, T.D. Noakes and M.I. Lambert. A novel submaximal test to monitor and predict cycling performance. *British Journal of Sports Medicine*, Epub (ahead of publication), 2009

## ABSTRACT

**Objective:** The purpose of this study was to determine the reliability and predictive value of performance parameters measured by a new novel submaximal cycle protocol, on peak power and endurance cycling performance in well-trained cyclists.

**Methods:** Seventeen well-trained competitive male road racing cyclists completed four peak power output tests (PPO) and four 40km time trials (40km TT). Before each test all cyclists performed a novel submaximal cycle test (LSCT). Parameters associated with performance such as power, speed, cadence and rate of perceived exertion (RPE) were measured during the 3 stages of the test when cyclists rode at workloads coinciding with fixed predetermined heart rates. Heart rate recovery (HRR) was measured after the last stage of the test. **Results:** Parameters measured during the second and third stage of the LSCT were highly reliable (Intraclass correlation range:  $R = 0.85 - 1.00$ ) with low typical error of measurements (TEM-range: 1.3 - 4.4%). Good relationships were found between the LSCT and cycling performance measured by the PPO and 40km TT tests. Mean power had stronger relationships with measures of cycling performance during the second ( $r = 0.80 - 0.89$ ) and third stage ( $r = 0.91 - 0.94$ ) of the LSCT than HRR ( $r = 0.55 - 0.68$ ). **Conclusions:** The LSCT is a reliable novel test which is able to predict peak and endurance cycling performance from submaximal power, RPE and HRR in well-trained cyclists. As these parameters are able to detect meaningful changes more accurately than  $VO_{2max}$ , the LSCT has the potential to monitor cycling performance with more precision than other current existing submaximal cycle protocols.

### Keywords:

LSCT • submaximal testing • cycling • monitoring • performance • heart rate recovery

## INTRODUCTION

Monitoring changes in performance of well-trained cyclists is necessary to determine the optimal balance between the training load and recovery. Two tests widely used to monitor and predict cycling performance are the peak power output test (PPO) and the 40km time trial test (40km TT) (Jeukendrup 2002; Lucia *et al.* 2000; Mujika and Padilla 2001). Both these tests are reliable and able to detect small meaningful differences ( $< 1\%$ ) in the day-to-day performance of well-trained cyclists, when the tests are conducted under well controlled circumstances (Lamberts *et al.* 2009c). However, the maximal and high intensity effort associated with both tests may interfere with the prescribed training program and preparation for races of well-trained and elite cyclists. Therefore, it is impractical to conduct these tests on a weekly or even monthly basis as would be required for on-going monitoring. As a result these tests are often only conducted 2 or 3 times each year during the rest period, the pre-competition period and sometimes once during the competition period.

In an attempt to monitor athletes and predict performance more regularly, submaximal tests have been used since the 1950's. The Cooper test (1968) is an example of one of the first submaximal tests to be widely used to predict performance of runners. In this test subjects are asked to cover as much distance as possible in 12 minutes. The total distance is used to predict maximal oxygen uptake capacity ( $VO_{2max}$ ) and endurance exercise capacity (Cooper 1968). A variety of protocols (walking and running) have evolved from this test. Examples of these adapted submaximal tests are the six-minute walk test (ATS Statement 2002; Butland *et al.* 1982), the shuttle walk test (Singh *et al.* 1992) and the Rockport Fitness Walk test (Kline *et al.* 1987). More recently a submaximal running test (HIMS) has been developed to monitor changes in training status through the measurement of heart rate recovery (HRR) (Borresen and Lambert 2007; Lamberts *et al.* 2004).

The development of submaximal cycle protocols also began in the 1950's with the Åstrand test (Åstrand and Ryhming 1954) and later the Physical Work Capacity 170 (WPC 170) test (Haber *et al.* 1976). Although gender and age specific equations were developed to improve the accuracy of the  $VO_{2max}$  predicted in the general

population from these tests (American College of Sports Medicine 2007; Hartung *et al.* 1995), the predicted  $\text{VO}_{2\text{max}}$  in well-trained cyclists still seems to be underestimated by approximately  $8.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  (Hartung *et al.* 1993). However this may not be relevant for monitoring changes in performance associated with training, as  $\text{VO}_{2\text{max}}$  has a limited accuracy to detect meaningful changes in well-trained cyclists (Lamberts *et al.* 2009c; Noakes 2008).

The development of devices such as cycle ergometers and heart rate monitors has provided the opportunity to measure a wider range of variables which may be associated with performance including for example power, cadence, cycling efficiency, heart rate recovery and heart rate variability (Lamberts *et al.* 2009a; Lamberts *et al.* 2009c). This offers the potential of developing a new type of submaximal cycle test which uses other variables than  $\text{VO}_{2\text{max}}$  as a predictor of cycling performance. If these variables who have shown to have lower typical errors of measurements (Lamberts *et al.* 2009c) are indeed able to predict cycling performance, such a test has the potential to monitor changes in cycling performance more accurately.

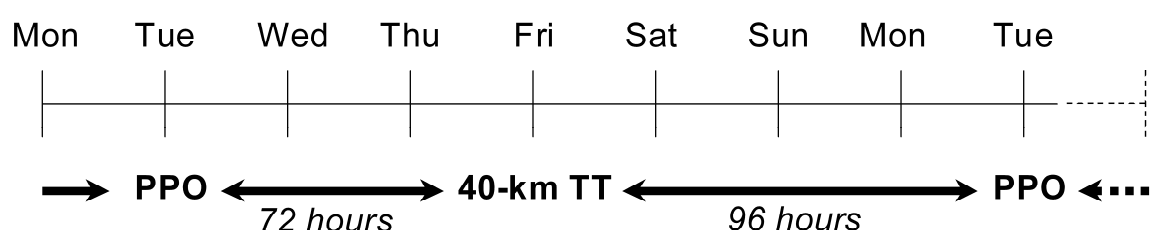
Therefore the aim of this study was to determine the reliability and predictive value of parameters measured during a novel submaximal cycle protocol (Lamberts *et al.* 2009c), on peak power and endurance cycling performance in well-trained cyclists. Based on the linear relationship between heart rate, exercise intensity and oxygen consumption (Arts and Kuipers 1994), we hypothesized that other variables as power are able to predict cycling performance accurately.

## METHODS

### ***Recruitment***

Seventeen well-trained competitive male road racing cyclists, who were all engaged in preseason base training and between the age of 18 and 40 years, were recruited for the study. All subjects completed a Physical Activity Readiness Questionnaire (PAR-Q) (American College of Sports Medicine 2007) and were interviewed about their training history after which an informed consent was signed. Inclusion criteria for

the study were a minimum of 6 training hours per week over the 6 week period before the trial and a minimum competitive cycling background of at least 3 years. The study was approved by the Ethics and Research Committee of the Faculty of Health Sciences of the University of Cape Town. The data presented in this paper was part of a larger study of which a part has already been published (Lamberts *et al.* 2009c). However whereas the previous publication focussed on measurement error around 40km TT's and peak power output tests, this study focuses on the reliability and predictive power of the LSCT.



**Figure 6.1** A schematic presentation of a testing week including the recovery times between the PPO and 40km TT tests.

\* Subjects were allowed to postpone one PPO and one 40km TT during the 5 week period (see also 'method' section)

### Study design

As previously described (Lamberts *et al.* 2009c), each subject completed four PPO tests (including respiratory gas analysis for oxygen consumption) and four 40km TT tests over a period of 5 consecutive weeks (Figure 1). Before each test subjects were questioned about 'sport injuries', 'sleeping patterns', 'use of medication', 'caffeine use', 'general fatigue' and 'muscle soreness' (Lamberts *et al.* 2009c). In addition a submaximal test (LSCT, described below) was performed. The initial 40km TT test and PPO test were used to familiarise the subjects and to establish the correct intensity of the warm-up protocol (see warm-up protocol) and were not included in the data analysis. Subjects were allowed to postpone both tests once during the 5 week period if they were able to provide a valid reason. Valid reasons for postponement included not feeling physically well (e.g. sore throat, coughing), not being able to start the testing at the required time due to unforeseen events (e.g. traffic holdups, power cuts) or inadequate sleep prior to the test, as described in Lamberts *et al.* (2009c). Before each test all subjects were questioned about possible confounding performance factors as for example the usage of caffeine. During the



testing period the cyclists were asked to maintain their training load constant, so that their training status was constant throughout the study.

### *Preliminary testing*

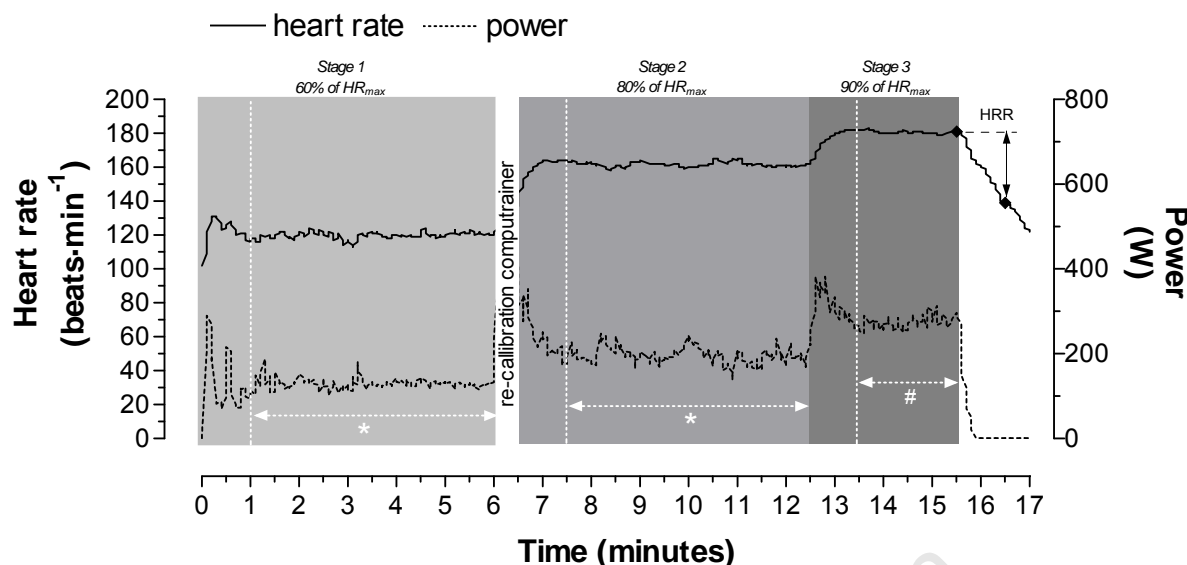
Anthropometric data including height, weight and seven skinfolds (triceps, biceps, supra-iliac, sub-scapular, calf, thigh and abdomen) (Ross and Marfell-Jones 1991) were obtained at the start of the study. Body fat was determined as the sum of seven skinfolds and also as a percentage of body mass (Durnin and Womersley 1974). Before each testing and training session cyclists were weighed to check for any significant changes in body mass which might reflect changes in their hydration status (Lamberts *et al.* 2004; Montain and Coyle 1992).

### *Calibration protocol*

The rear wheel tire of the subject's own bicycle was inflated to 800 kPa and the bicycle was mounted, by a rear axle quick release mechanism, to an cycle ergometer (Computrainer™ Pro 3D, RacerMate, Seattle, USA). Before the start of a standardized warm-up protocol the contact pressure of the load-generator against the rear wheel was calibrated to 0.88-0.93 kg. Six minutes into the warm-up protocol, by which time the tire had warmed-up, the load generator was re-calibrated to 0.88 - 0.93 kg as recommended by Davison *et al.* (2007).

### ***LSCT - submaximal cycle protocol***

The Lamberts and Lamberts Submaximal Cycle Test (LSCT), which has been developed to monitor changes in training status (Lamberts *et al.* 2009c) and detect the symptoms of overreaching, was used as the warm-up protocol before all performance tests. The total duration of the LSCT is 17 minutes, during which time subjects are asked to cycle at intensities which elicit target heart rates of 60% (stage 1), 80% (stage 2) and 90% (stage 3) of their maximum heart rate ( $HR_{max}$ ) (Figure 6.2).



**Figure 6.2** Representation of the data of an arbitrary cyclist's heart rate response and power profile during the Lamberts and Lambert submaximal cycle test (LSCT).

\* 5 minute period over which performance parameters were analyzed, # 2 minute period over which performance parameters were analyzed.

Target heart rates for each of the different stages of the LSCT were calculated from the first PPO test in which  $HR_{max}$  was determined (Lamberts *et al.* 2009c). Following calibration a flat course profile mimicking normal road circumstances was loaded into the Computrainer<sup>TM</sup> system. Thereafter subjects were asked to change their front derailleur to the 'small' chain ring, after which the LSCT was started. During the LSCT, subjects were allowed to alter their cadence and/or change gears on their rear derailleur within each stage in an attempt to elicit the correct target heart rate ( $\pm 1$  beats $\cdot$ min<sup>-1</sup>). In stage 1 of the LSCT (0.00 - 6.00 min) subjects were asked to elicit a target heart rate equal to 60% of their personal  $HR_{max}$ . Following this stage subjects were asked to change their front derailleur to the 'large' chain ring, while the Computrainer<sup>TM</sup> system was recalibrated for accuracy purposes (6.00-6.30 min). During stage 2 of the LSCT (6.30-12.30 min), subjects were asked to elicit a target heart rate equal to 80% of their  $HR_{max}$ . Directly after this stage (stage 3; 12.30-15.30 min) subjects increased the workload to elicit a heart rate of 90% of  $HR_{max}$ . Immediately thereafter subjects were asked to stop cycling and sit straight up, so that HRR data could be captured over the final 90 second of the LSCT (15.30-17.00). Although HRR analysis was performed over a 60 second period, as described before by Lamberts *et al.* (2004), the heart rate data were measured over 90 second to ensure that there were no missing data. During the LSCT, power, speed and cadence were measured continuously, while a rating of perceived exertion (RPE)

(Davison *et al.* 2007) for each stage was recorded 30 seconds before the end of each stage. Target heart rates for each of the different stages of the LSCT were calculated from the first PPO test in which  $HR_{max}$  was determined (Lamberts *et al.* 2009c).

### **Peak power output test (PPO)**

The PPO tests which included respiratory gas analysis ( $VO_{2max}$ ), were performed as previously described by Lamberts *et al.* (2009c) and started exactly 3 minutes after the LSCT. Maximal peak power output was determined as the mean power output during the final minute of the PPO test whereas  $VO_{2max}$  ( $ml \cdot kg^{-1} \cdot min^{-1}$ ) was determined as the highest recorded reading for 30 seconds during this test (Lamberts *et al.* 2009c).

### **40km time trial (40km TT)**

The 40km TT tests were started 5 minutes after completing the LSCT on a simulated 40km flat TT course during which any type of feedback, except for completed distance, was withheld from the subject. No verbal encouragement was given during the time trial, except for during the last kilometre when the distance was counted down in 100 m sections and during the last hundred meters in 10 m sections (Lamberts *et al.* 2009c). Thirty minutes after finishing the 40km TT, subjects gave an overall rating of perceived exertion for the 40km TT (6-20 Borg-scale) (Davison *et al.* 2007).

### **Data collection and analysis**

Power output, speed, cadence and elapsed time were measured during all trials and stored by the Computrainer<sup>TM</sup> software at a rate of 34 Hz. Heart rate during these tests were measured with Suunto T6 heart rate monitors (Suunto Oy, Vantaa, Finland) and data were stored every 2 seconds. Oxygen uptake ( $VO_2$ ) and  $CO_2$  production ( $VCO_2$ ) were measured with an on-line breath-by-breath gas analyser and pneumotach (Oxycon, Viasis, Hoechberg, Germany) and stored as average values over 8 breaths.

Due to the slow half life of changes in heart rate (Achten and Jeukendrup 2003) and subjects having to make fine adjustments to their work load to reach a specific heart

rate during the warm-up, the heart rate and performance data in the first minute of each stage of the LSCT were excluded from analysis. Therefore, average performance and heart rate values were calculated over a five minute period (from minute 1:00 to 6:00 and from 7:30 to 12:30 (min:s)) for stage 1 and 2 respectively and for a two minute period (13:30-15:30 min:s) for stage 3. Performance and heart rate data from the PPO test and the 40km TT test were analyzed for the full period of the data capture.

Analysis of performance data was performed using CyclingPeaks<sup>TM</sup> analysis software (WKO+ edition, Version 2.1, 2006, Lafayette, CO, USA) and the Computrainer<sup>TM</sup> coaching software (Version 1.5.308, RacerMate, Seattle, USA). Heart rate data were analysed with Suunto Training Manager (Version 2.1.0.3, Suunto Oy, Vantaa, Finland).

### ***Statistical Analysis***

The data were analysed with STATISTICA version 8.0 (Stat-soft Inc., Tulsa, OK, USA) for any statistical significance ( $P < 0.05$ ). All data are expressed as means  $\pm$  standard deviation ( $X \pm s$ ). The mean physiological responses of all six submaximal cycle tests, conducted before each PPO and 40km TT, were compared by using a repeated measures analysis of variance (ANOVA). Reliability for each variable was also assessed by calculating interclass correlation coefficient (ICC) and the 95% confidence intervals (Vincent 1995). Typical error of the measurement and typical error of the measurement as a percentage (%), expressed as a % of the mean score, were calculated with 90% confidence intervals, using a spreadsheet downloaded from [www.newstats.org](http://www.newstats.org).

## RESULTS

The dataset of 2 cyclists were excluded from analysis because they either did not complete the trial or unintentionally began using a medically prescribed drug which potentially enhances performance (Swart *et al.* 2008). The subject characteristics remaining of the remaining 15 cyclists are shown in Table 6.1, while subjects trained  $10 \pm 3 \text{ h}\cdot\text{wk}^{-1}$  with a competitive cycling history of  $7 \pm 3$  years (Lamberts *et al.* 2009c).

**Table 6.1** General characteristics of the 15 well-trained cyclists.

Variable	$\bar{X} \pm s$
Age (years)	$31 \pm 4$
Body mass (kg)	$78.6 \pm 8.3$
Stature (m)	$1.82 \pm 0.08$
Percentage body fat (%)	$16.3 \pm 3.6$
Skinfolds (mm)	$70.1 \pm 26.6$
PPO (W)	$382 \pm 48$
PPO ( $\text{W}\cdot\text{kg}^{-1}$ )	$4.87 \pm 0.51$
$\text{VO}_{2\text{max}}$ ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ )	$56.91 \pm 6.77$
40km TT (min.s)	$66.11 \pm 3.39$

Nine cyclists completed the testing within 4 weeks while, six riders completed the testing within 5 weeks. A questionnaire which was completed before each test revealed that none had consumed caffeine within the last 3 hours before the test and all subjects had maintained a similar dietary pattern. Furthermore, none reported any symptoms of general fatigue or muscle soreness, slept well the night before each test, were wearing the same cycling outfits during all tests and made no changes to their bicycle set-ups.

All testing was performed on the same day of the week and at about the same time (within 1 hour) with stable climatic conditions ( $21.7 \pm 0.7^\circ\text{C}$ ,  $52 \pm 4\%$  relative humidity,  $101.8 \pm 0.7 \text{ kPa}$ ). The body mass of the cyclists remained stable within  $1.0 \pm 0.4\%$  ( $0.8 \pm 0.3 \text{ kg}$ ) throughout the study.

## LSCT

All subjects were able to closely regulate their heart rate by adjusting their exercise intensity during the 3 different stages of the LSCT.

**Table 6.2:** Mean physiological changes during the submaximal cycle tests (LSCT) which were performed before each PPO test and 40km TT. The data are expressed as mean  $\pm$  SD . Data are expressed as the ICC, typical error of measurement (**TEM**) and typical error of measurement as a CV (%) (**TEM%**). Data in brackets are the 90% CI of that variable.

	LSCT 1	LSCT 2	LSCT 3	LSCT 4	LSCT 5	LSCT 6	Mean	ICC	TEM	TEM (%)
<b>Stage 1 (60% of maximal heart rate)</b>										
Average power (W)	114 $\pm 24$	114 $\pm 23$	124 $\pm 28$	111 $\pm 22$	119 $\pm 26$	118 $\pm 22$	117 $\pm 21$	<b>0.91</b> (0.83-0.96)	<b>14.4</b> (12.6–16.7)	<b>12.4</b> (10.8–14.6)
Expressed as an % of PPO	30 $\pm 5$	30 $\pm 5$	33 $\pm 7$	29 $\pm 5$	32 $\pm 7$	32 $\pm 7$	31 $\pm 5$	<b>0.90</b> (0.81-0.91)	---	---
Average speed (km·h <sup>-1</sup> )	25 $\pm 3$	25 $\pm 3$	26 $\pm 3$	24 $\pm 3$	25 $\pm 3$	25 $\pm 2$	24 $\pm 2$	<b>0.93</b> (0.84-0.97)	<b>1.3</b> (1.1–1.5)	<b>5.3</b> (4.6–6.2)
Cadence (rpm)	86 $\pm 7$	84 $\pm 8$	88 $\pm 6$	84 $\pm 8$	86 $\pm 7$	85 $\pm 7$	86 $\pm 6$	<b>0.91</b> (0.80-0.97)	<b>4.3</b> (3.8–5.0)	<b>5.2</b> (4.5–5.0)
RPE (units)	8 $\pm 1$	8 $\pm 1$	8 $\pm 1$	8 $\pm 1$	8 $\pm 1$	8 $\pm 1$	8 $\pm 1$	<b>0.88</b> (0.78-0.95)	<b>0.8</b> (0.7–1.0)	---
<b>Stage 2 (80% of maximal heart rate)</b>										
Average power (W)	231 $\pm 33$	230 $\pm 32$	239 $\pm 31$	224 $\pm 27$	225 $\pm 29$	230 $\pm 29$	230 $\pm 29$	<b>0.98</b> (0.96-0.99)	<b>8.5</b> (7.5–9.9)	<b>3.7</b> (3.3–4.4)
Expressed as a % of PPO	61 $\pm 5$	61 $\pm 5$	63 $\pm 5$	59 $\pm 4$	59 $\pm 5$	61 $\pm 4$	60 $\pm 4$	<b>0.94</b> (0.88-0.98)	---	---
Average speed (km·h <sup>-1</sup> )	34 $\pm 2$	34 $\pm 2$	34 $\pm 2$	34 $\pm 2$	34 $\pm 2$	34 $\pm 2$	34 $\pm 2$	<b>0.98</b> (0.96-0.99)	<b>0.5</b> (0.5–0.6)	<b>1.6</b> (1.4–1.9)
Cadence (rpm)	90 $\pm 8$	91 $\pm 9$	93 $\pm 5$	90 $\pm 7$	90 $\pm 8$	91 $\pm 6$	91 $\pm 6$	<b>0.93</b> (0.86-0.97)	<b>4.0</b> (3.5–4.6)	<b>4.4</b> (3.8–5.1)
RPE (units)	12 $\pm 1$	13 $\pm 1$	13 $\pm 1$	12 $\pm 1$	12 $\pm 1$	13 $\pm 1$	12 $\pm 1$	<b>0.85</b> (0.73-0.94)	<b>0.8</b> (0.7–0.9)	---
<b>Stage 3 (90% of maximal heart rate)</b>										
Average power (W)	304 $\pm 41$	304 $\pm 40$	306 $\pm 40$	303 $\pm 41$	303 $\pm 38$	305 $\pm 40$	304 $\pm 40$	<b>1.00</b> (0.99-1.00)	<b>4.6</b> (4.0–5.3)	<b>1.5</b> (1.3–1.8)
Expressed as a % of PPO	80 $\pm 4$	80 $\pm 3$	80 $\pm 4$	79 $\pm 4$	79 $\pm 3$	80 $\pm 3$	80 $\pm 3$	<b>0.98</b> (0.96-0.99)	---	---
Average speed (km·h <sup>-1</sup> )	38 $\pm 2$	38 $\pm 2$	38 $\pm 2$	38 $\pm 2$	38 $\pm 2$	38 $\pm 2$	38 $\pm 2$	<b>0.99</b> (0.99-1.00)	<b>0.5</b> (0.4–0.6)	<b>1.3</b> (1.1–1.5)
Cadence (rpm)	95 $\pm 7$	96 $\pm 8$	94 $\pm 7$	95 $\pm 9$	95 $\pm 7$	95 $\pm 7$	95 $\pm 7$	<b>0.96</b> (0.92-0.98)	<b>3.5</b> (3.1–4.1)	<b>3.7</b> (3.2–4.3)
RPE (units)	16 $\pm 1$	16 $\pm 1$	16 $\pm 1$	16 $\pm 1$	16 $\pm 1$	16 $\pm 1$	16 $\pm 1$	<b>0.86</b> (0.74-0.94)	<b>0.7</b> (0.6–0.8)	---
<b>Heart rate recovery period</b>										
Peak HR (beats·min <sup>-1</sup> )	171 $\pm 6$	170 $\pm 5$	170 $\pm 6$	171 $\pm 5$	170 $\pm 6$	170 $\pm 5$	170 $\pm 5$	<b>0.99</b>	<b>1.3</b> (1.1–1.5)	<b>0.8</b> (0.7–0.9)
1 min HR (beats·min <sup>-1</sup> )	127 $\pm 12$	127 $\pm 10$	126 $\pm 9$	127 $\pm 10$	126 $\pm 9$	126 $\pm 9$	126 $\pm 9$	<b>0.99</b>	<b>2.2</b> (1.9–2.6)	<b>1.8</b> (1.6–2.1)
HRR (beats)	44 $\pm 10$	43 $\pm 10$	45 $\pm 9$	43 $\pm 10$	44 $\pm 9$	44 $\pm 9$	44 $\pm 9$	<b>0.99</b>	<b>1.6</b> (1.4–1.9)	<b>4.2</b> (3.7–4.9)

\* average heart rate over the last 5 minutes # average heart rate over the last 2 minutes

Mean fluctuations in heart rates were  $0 \pm 1$  beats (range, -3 to 2 beats) at 60% of  $HR_{max}$ ,  $0 \pm 1$  beats (range, -1 to 2 beats) at 80% of  $HR_{max}$  and  $0 \pm 1$  beats (range, -1 to 1 beat) while cycling at 90% of  $HR_{max}$ . Workload intensities corresponded to  $31 \pm 5\%$ ,  $60 \pm 4\%$  and  $80 \pm 3\%$  of PPO, respectively, while ratings of perceived exertion increased progressively with each workload ( $8 \pm 2$ ,  $11 \pm 1$  and  $16 \pm 1$ , respectively) as expected.

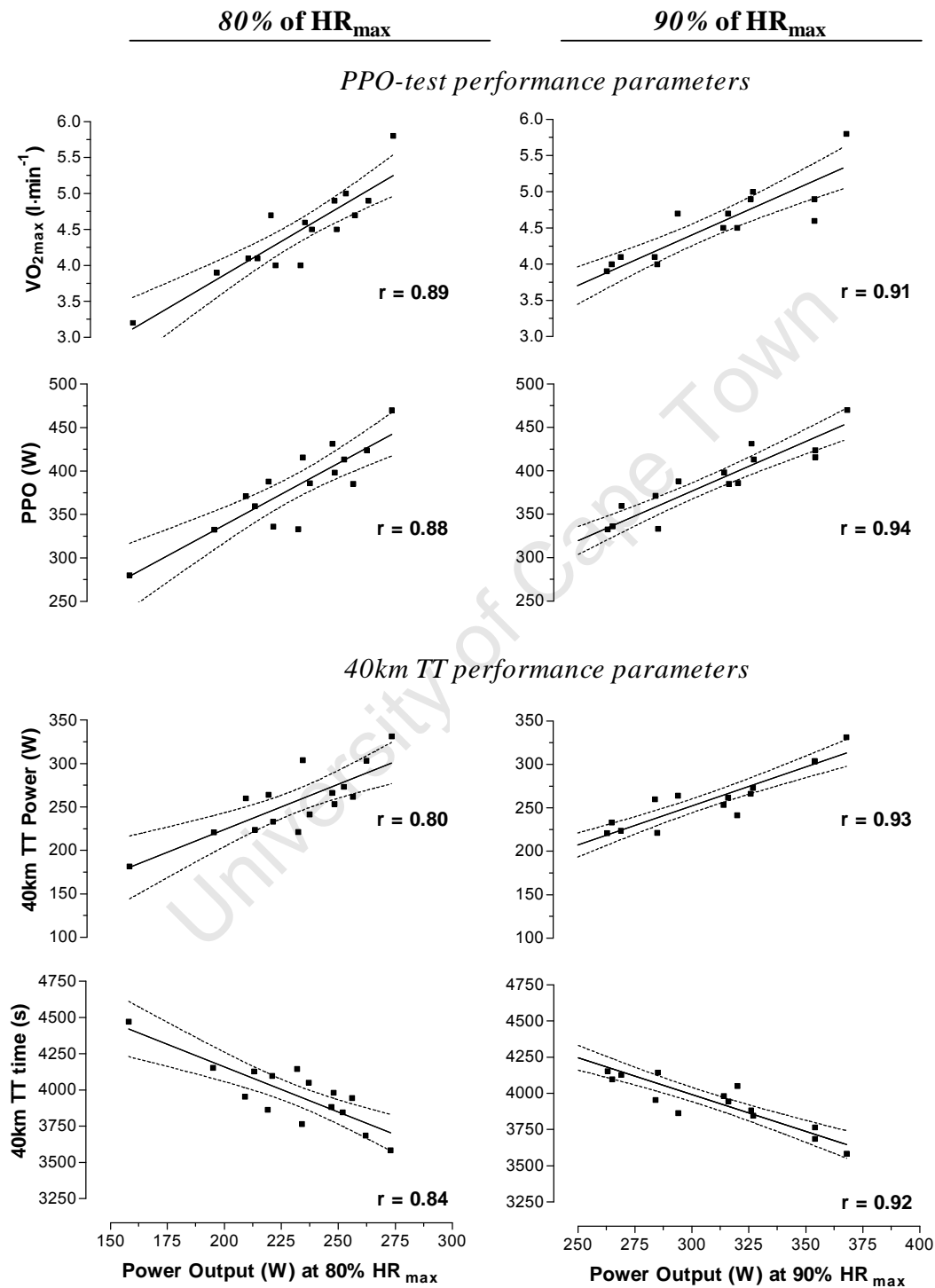
Mean physiological responses of the cyclists during the LSCT are shown in Table 6.2. In addition, intraclass correlation coefficients (ICC), typical error measurement (TEM) and typical error measurement error as CV (%) for the physiological responses are shown in Table 6.2. The highest ICC and lowest TEM were found during stage 3 (90% of  $HR_{max}$ ) of the LSCT. The highest overall ICC ( $R = 1.00$ ) occurred for mean power measured during the last stage at 90% of  $HR_{max}$  with a TEM of 4.6 W (1.5%). The TEM of speed and cadence during this stage was  $0.5 \text{ km}\cdot\text{h}^{-1}$  (1.5%) and 3.5 rpm (3.7%) respectively. Absolute and relative heart rate recovery after the LSCT and their respective ICC and TEMs are also shown in Table 6.2.

**Table 6.3** Mean time and physiological changes during the three peak power output tests and 40km time trials. The data are expressed as  $X \pm SD$ .

Variable	Test 1	Test 2	Test 3	Mean
<b>Peak power output test</b>				
PPO (W)	$381 \pm 47$	$382 \pm 48$	$382 \pm 49$	$382 \pm 48$
PPO ( $\text{W}\cdot\text{kg}^{-1}$ )	$4.86 \pm 0.50$	$4.87 \pm 0.53$	$4.87 \pm 0.49$	$4.87 \pm 0.51$
$VO_{2max}$ ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ )	$56.49 \pm 7.13$	$56.71 \pm 6.63$	$57.41 \pm 6.63$	$56.91 \pm 6.77$
Max heart rate ( $\text{beats}\cdot\text{min}^{-1}$ )	$190 \pm 5$	$190 \pm 7$	$189 \pm 6$	$190 \pm 6$
<b>40km time trial test</b>				
Time (s)	$3980 \pm 229$	$3964 \pm 215$	$3967 \pm 215$	$3972 \pm 220$
Average HR ( $\text{beats}\cdot\text{min}^{-1}$ )	$173 \pm 6$	$174 \pm 5$	$173 \pm 5$	$173 \pm 5$
Average HR% of maximum HR	$91 \pm 3$	$92 \pm 3$	$91 \pm 3$	$91 \pm 3$
Average speed ( $\text{km}\cdot\text{h}^{-1}$ )	$36.3 \pm 2.0$	$36.4 \pm 2.0$	$36.4 \pm 1.9$	$36.3 \pm 2.0$
Average power (W)	$254 \pm 39$	$257 \pm 39$	$256 \pm 38$	$254 \pm 39$
Cadence (rpm)	$92 \pm 7$	$91 \pm 8$	$92 \pm 6$	$92 \pm 7$
RPE (units)	$17 \pm 1$	$18 \pm 1$	$18 \pm 1$	$17 \pm 1$

### PPO test and the 40km TT

The mean physiological responses of the cyclists during the three PPO tests and 40km TT's are presented in Table 6.3.



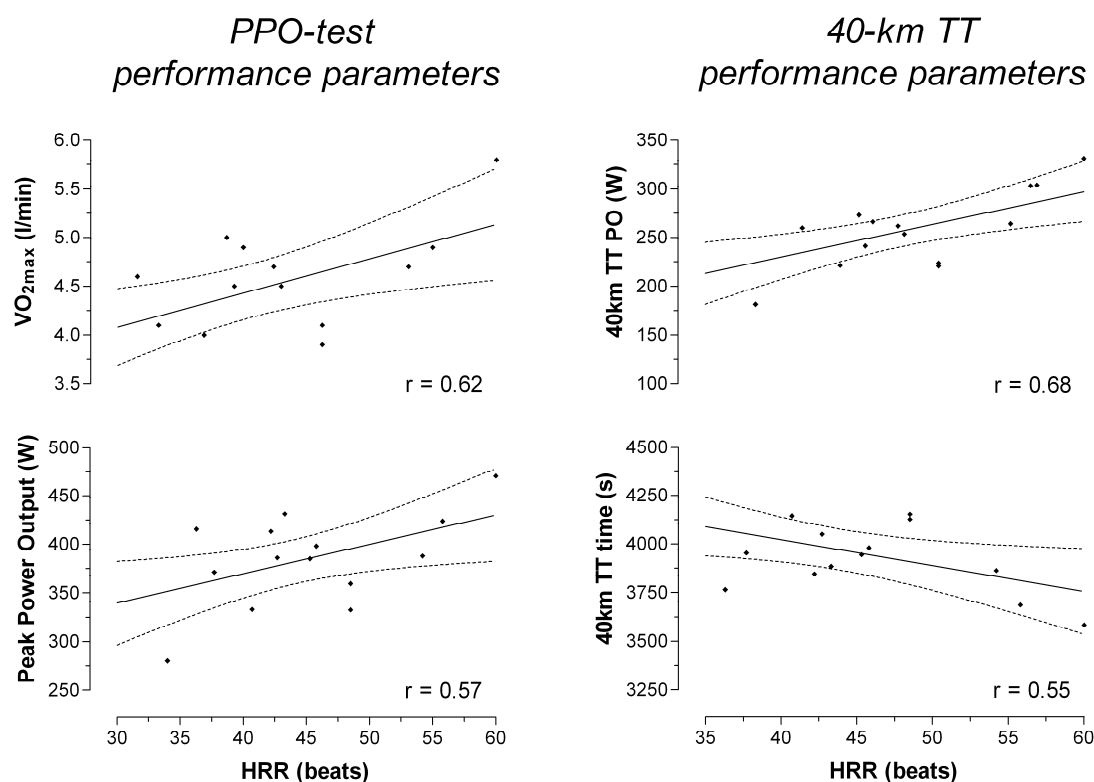
**Figure 6.3** The predictive value of the mean power output when cycling at 80 and 90%  $HR_{max}$  during the LSCT on performance parameters  $VO_{2max}$ , PPO, average 40km TT power and 40km TT time.



High ICC's and low TEM's were found during the PPO test for peak power output ( $R = 1.00$ ,  $TEM = 0.9\%$ ), relative peak power output ( $R = 1.00$ ,  $TEM = 1.1\%$ ) and maximum oxygen uptake ( $VO_{2max}$ ) ( $R = 0.99$ ;  $TEM = 2.2\%$ ). During the 40km TT there were high ICC and low TEMs for 40km TT time ( $R = 0.99$ ;  $TEM = 0.7\%$ ), average power ( $R = 1.00$ ;  $TEM = 1.7\%$ ) and speed ( $R = 1.00$ ,  $TEM = 0.6\%$ ). The lowest ICC's were found for cadence ( $r = 0.93$ ,  $TEM = 3.5\%$ ) and RPE ( $r = 0.90$ ,  $TEM = 2.8\%$ ). The average heart rate during the 40km TT was 92% of  $HR_{max}$ .

### ***Relationships between LSCT and performance parameters***

Relationships between mean power during the second (80% of  $HR_{max}$ ) and third stage (90% of  $HR_{max}$ ) of the LSCT and the performance parameters during the PPO test ( $VO_{2max}$  and PPO) and the 40km TT (40km TT time and 40km TT PO) are shown in Figure 6.3. Although good relationships occurred between mean PPO during the second stage (80% of  $HR_{max}$ ) and the performance parameters, stronger relationships were found between these performance parameters and mean power output during the third stage (90% of  $HR_{max}$ ).



**Figure 6.4** Correlation between HRR measured as part of the LSCT and absolute and relative performance parameters  $VO_{2max}$ , PPO, average 40km TT power and 40km TT time.

The relationships between HRR and the performance parameters are shown in Figure 6.4. Weak relationships occurred between HRR and peak power and endurance performance. Although the relationship between performance parameters and HRR was significant, relationships between the performance parameters and the mean power during the second (80% of  $HR_{max}$ ) and third stage (90% of  $HR_{max}$ ) of the LSCT were substantially better than the HRR relationships.

## DISCUSSION

The first relevant finding of this study was that the LSCT test was truly submaximal, as confirmed by the workloads (31%, 60% and 80% of PPO, respectively) and rating of perceived exertions (RPE: 8, 12 and 16, respectively). In addition the low TEM in the RPE's during the first stage of the LSCT, low TEM in 40km TT and PPO results (Lamberts *et al.* 2009c) and no reports of fatigue and/or muscle soreness before the LSCT (which was performed twice per week), indicates that the LSCT does not interfere with 'normal' training habits. This was also confirmed by the anecdotal comments we received from the subjects. These factors suggest that the test has positive practical attributes for monitoring cyclists on a regular basis. In contrast a maximal or near maximal endurance test, which by definition has an exhausting character, would interfere with the cyclists' training and racing programme and therefore cannot be administered as frequently as a submaximal test (Jeukendrup 2002). All cyclists were able to adhere to the protocol for the LSCT and maintained their heart rates within a few beats of their target heart rate for each workload. As the exercise intensity increased the variation in heart rate decreased with the variation being reduced to  $\pm 1$  beat at the workload corresponding to 90% of  $HR_{max}$ , which indicates that heart rate is easier to control at higher intensities. This is in accordance with earlier published research work in our laboratory on physically active subjects undergoing an incremental submaximal running test (Lamberts *et al.* 2004; Lamberts and Lambert 2009).

The second finding of this study was that all performance parameters measured during the second and third stage of the LSCT were highly repeatable (ICC range: 0.85 – 1.00) with relatively low TEM (TEM range: 1.3 - 4.4%) (Lamberts *et al.* 2009a).

The overall highest repeatability with the lowest TEM occurred during the third stage of the LSCT (90% of  $HR_{max}$ ), where mean power output and mean speed had the lowest TEM's (1.5 and 1.3%, respectively). In addition, the measurement of HRR was also reliable. HRR, which is a marker of autonomic function (Borresen and Lambert 2008; Buchheit *et al.* 2007; Buchheit and Gindre 2006), has recently been associated with a change in prescribed training load (Borresen and Lambert 2007) and training status (Lamberts *et al.* 2009b). HRR, with an unchanged training status, over the duration of the testing period only varied by only 5 beats per minute (see also Table 6.3). This is similar to what has been reported before (Brisswalter and Legros 1994; Lamberts *et al.* 2004; Lamberts and Lambert 2009) and smaller than what was measured as a result of an improved training status (Buchheit *et al.* 2008; Lamberts *et al.* 2009a; Sugawara *et al.* 2001), indicating that there is sufficient precision in the measurement of HRR to detect small meaningful changes.

The third finding of this study describes the relationship between mean power and HRR measured during the LSCT, and peak power (PPO) and endurance (40km TT) cycle performance. Although good relationships were found between the parameters measured during second stage of the LSCT (80%  $HR_{max}$ ) and PPO and 40km TT performance ( $r = 0.80-0.89$ ), an even better relationship was found with mean power during the third stage of the LSCT (90% of  $HR_{max}$ ) ( $r = 0.91-0.94$ ).

Based on the understanding that heart rate decreases during exercise at a similar workload as training status improves (Wilmore *et al.* 1996), it is a given that during exercise at the same heart rate, workload will increase. This is supported by Lucia *et al.* (2000) who showed that submaximal power, at ventilatory threshold 1 and 2 and lactate threshold, increased as training status improved while the heart rates at these stages remained unchanged (Lucia *et al.* 2000). While no single parameter has been identified as a reliable marker of training-induced fatigue or symptoms of overreaching, it is generally accepted that non-functional overreaching is associated with a decrement in performance (Meeusen *et al.* 2006). In addition most overtraining studies report a decrease in submaximal and maximal heart rates with the manifestation of fatigue (Halsen *et al.* 2002; Jeukendrup *et al.* 1992; Lehmann *et al.* 1991; Urhausen *et al.* 1998), which would possibly lead to a increase in power during stage 2 and 3 of the LSCT because the predetermined submaximal heart rates

during each of these workloads would be harder to elicit. Based on the good correlations between average power during stage 2 and 3 of the LSCT and performance parameters, a change in mean power could possibly reflect changes in training status in a practical, meaningful way.

In contrast to power, HRR showed a weaker relationship to PPO and 40km TT performance. This can possibly be explained by the homogeneity of our cyclists who were all well-trained and in which genetic polymorphisms in acetylcholine receptor M2 (CHRM2) can explain inter-individual differences in HRR (Hautala *et al.* 2006). Although there was a relatively weak relationship between HRR and cycling performance, changes in HRR have recently shown to track well with changes in performance parameters (Lamberts *et al.* 2009c) and seems to be associated with a blunted improvement in endurance performance parameters (Lamberts *et al.* 2009b). Therefore a combination of a change in HRR with a change in power and RPE's during the LSCT, might provide more useful information for monitoring fatigue and predicting performance than other current submaximal cycle protocols which rely on changes in predicted  $\text{VO}_{2\text{max}}$ .

### **Summary and conclusion**

In summary, the goal of this study was to identify markers arising from submaximal exercise which would accurately reflect cycling performance. Such markers would provide a practical method for coaches and scientists to accurately monitor cycling performance. The LSCT, in which heart rate is fixed at a predetermined submaximal level, has the potential to detect subtle changes in performance as a result of training-induced fatigue. In addition, monitoring the cumulative fatigue could contribute to detecting the status of functional or non-functional overreaching. Collectively, these factors will be useful in maintaining the balance between training load and recovery with the purpose of achieving the most optimal training status. In particular, the LSCT could indicate the development of fatigue by a combination of 3 parameters; 1) increased RPE levels; as subjects will have to work harder to elicit their heart rates to 90% of  $\text{HR}_{\text{max}}$ , 2) a sudden strong increase in mean power; as a higher workload is needed to elicit the target heart rates, 3) a change in HRR; based on deregulation of the autonomic nervous system (Borresen and Lambert 2007;

Lehmann *et al.* 1991). The precision of these markers in detecting and tracking fatigue will have to be determined in future research.

## ACKNOWLEDGEMENTS

The authors would like to thank all cyclists who participated in this study. This study was funded by the Medical Research Council of South Africa, Discovery Health and the University of Cape Town Research Unit for Exercise Science and Sports Medicine.

### What is already known on this topic:

Submaximal cycle tests such as the Åstrand and WPC 170 are reliable tests which are able to predict of  $VO_{2max}$  in a general population.

However, changes in  $VO_{2max}$  do not track with changes in cycling performance in well- trained cyclists. Therefore these test have a limited application and are not applicable for measuring small changes in cycling performance.

### What this study adds:

This study presents a novel submaximal cycle protocol (LSCT) which is reliable, has low typical errors of measurement, is able to predict cycling performance with reasonable accuracy and possibly can monitor the accumulation of fatigue.

Based on these findings, the LSCT has the potential to monitor cycling performance and training-induced fatigue with sufficient precision to be able to detect small but meaningful changes.

## REFERENCES

- ATS statement (2002): guidelines for the six-minute walk test. *Am J Respir Crit Care Med* 166: 111-117
- Achten J and Jeukendrup AE (2003) Heart rate monitoring: applications and limitations. *Sports Med* 33: 517-538
- American College of Sports Medicine (2007) Submaximal Exercise Tests. In: Whaley MH, Brubaker PH and Otto RM. (eds) *ACSM's Guidelines for Exercise Testing and Prescription*. Lippincott Williams & Wilkins, Baltimore, MD, USA, pp 70-74.
- Arts FJ and Kuipers H (1994) The relation between power output, oxygen uptake and heart rate in male athletes. *Int J Sports Med* 15: 228-231
- Åstrand PO and Ryhming I (1954) A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during sub-maximal work. *J Appl Physiol* 7: 218-221
- Borresen J and Lambert MI (2007) Changes in heart rate recovery in response to acute changes in training load. *Eur J Appl Physiol* 101: 503-511
- Borresen J and Lambert MI (2008) Autonomic control of heart rate during and after exercise - measurements and implications for monitoring training status. *Sports Med* 28: 633-646
- Brisswalter J and Legros P (1994) Daily stability in energy cost of running, respiratory parameters and stride rate among well-trained middle distance runners. *Int J Sports Med* 15: 238-241

- Buchheit M and Gindre C (2006) Cardiac parasympathetic regulation: respective associations with cardiorespiratory fitness and training load. *Am J Physiol Heart Circ Physiol* 291: H451-H458
- Buchheit M, Millet GP, Parisy A, Pourchez S, Laursen PB and Ahmaidi S (2008) Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Med Sci Sports Exerc* 40: 362-371
- Buchheit M, Papelier Y, Laursen PB and Ahmaidi S (2007) Noninvasive assessment of cardiac parasympathetic function: postexercise heart rate recovery or heart rate variability? *Am J Physiol Heart Circ Physiol* 293: H8-H10
- Butland RJ, Pang J, Gross ER, Woodcock AA and Geddes DM (1982) Two-, six-, and 12-minute walking tests in respiratory disease. *Br Med J (Clin Res Ed)* 284: 1607-1608
- Cooper KH (1968) A means of assessing maximal oxygen intake. Correlation between field and treadmill testing. *JAMA* 203: 201-204
- Davison RCR, Corbett J and Ansley L (2007) Influence of temperature and protocol on the calibration of the computrainer electromagnetically braked cycling ergometer. *J of Sports Sci* 25: 257-258
- Durnin JVGA and Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr* 32: 77-97
- Haber P, Schlick W, Schmid P and Mulac K (1976) Estimation of the performance spectrum of healthy adolescents by using the PWC 170 (Physical Work Capacity). *Acta Med Austriaca* 3: 164-166

- Halson SL, Bridge MW, Meeusen R, Busschaert B, Gleeson M, Jones DA and Jeukendrup AE (2002) Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* 93: 947-956
- Hartung GH, Blancq RJ, Lally DA and Krock LP (1995) Estimation of aerobic capacity from submaximal cycle ergometry in women. *Med Sci Sports Exerc* 27: 452-457
- Hartung GH, Krock LP, Crandall CG, Bisson RU and Myhre LG (1993) Prediction of maximal oxygen uptake from submaximal exercise testing in aerobically fit and nonfit men. *Aviat Space Environ Med* 64: 735-740
- Hautala AJ, Rankinen T, Kiviniemi AM, Makikallio TH, Huikuri HV, Bouchard C and Tulppo MP (2006) Heart rate recovery after maximal exercise is associated with acetylcholine receptor M2 (CHRM2) gene polymorphism. *Am J Physiol Heart Circ Physiol* 291: H459-H466
- Jeukendrup A (2002) High-performance cycling. Human Kinetics Publishers, Inc., Champaign, IL, USA.
- Jeukendrup AE, Hesselink MK, Snyder AC, Kuipers H and Keizer HA (1992) Physiological changes in male competitive cyclists after two weeks of intensified training. *Int J Sports Med* 13: 534-541
- Kline GM, Porcari JP, Hintermeister R, Freedson PS, Ward A, McCarron RF, Ross J and Rippe JM (1987) Estimation of  $VO_{2max}$  from a one-mile track walk, gender, age, and body weight. *Med Sci Sports Exerc* 19: 253-259
- Lamberts RP and Lambert MI (2009) Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. *J Strength Cond Res* 23: 1005-1010



- Lamberts RP, Lemmink KA, Durandt JJ and Lambert MI (2004) Variation in heart rate during submaximal exercise: implications for monitoring training. *J Strength Cond Res* 18: 641-645
- Lamberts RP, Swart J, Noakes TD and Lambert MI (2009a) Changes in heart rate recovery after high-intensity training in well-trained cyclists. *Eur J Appl Physiol* 105: 705-713
- Lamberts RP, Swart J, Noakes TD and Lambert MI (2009b) Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. *Scand J Med Sci Sports* (Epub; ahead of publ.)
- Lamberts RP, Swart J, Woolrich RW, Noakes TD and Lambert MI (2009c) Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status. *Int SportMed J* 10: 33-44
- Lehmann M, Dickhuth HH, Gendrich G, Lazar W, Thum M, Kaminski R, Aramendi JF, Peterke E, Wieland W and Keul J (1991) Training-overtraining. A prospective, experimental study with experienced middle- and long-distance runners. *Int J Sports Med* 12: 444-452
- Lucia A, Hoyos J, Perez M and Chicharro JL (2000) Heart rate and performance parameters in elite cyclists: a longitudinal study. *Med Sci Sports Exerc* 32: 1777-1782
- Meeusen R, Duclos M, Gleeson M, Rietjens GJ, Steinacker JM and Urhausen A (2006) Prevention, diagnosis and treatment of the overtraining syndrome. *Eur J Sport Sci* 6: 1-14
- Montain SJ and Coyle EF (1992) Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *J Appl Physiol* 73: 1340-1350

- Mujika I and Padilla S (2001) Physiological and performance characteristics of male professional road cyclists. *Sports Med* 31: 479-487
- Noakes TD (2008) Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *Br J Sports Med* 42: 551-555
- Ross WD and Marfell-Jones MJ (1991) Kinanthropometry. In: MacDougall JD, Wenger HA and Green HS. (eds) *Physiological Testing of the High Performance Athlete*. Champaign, IL: Human Kinetics, pp 223-308.
- Singh SJ, Morgan MD, Scott S, Walters D and Hardman AE (1992) Development of a shuttle walking test of disability in patients with chronic airways obstruction. *Thorax* 47: 1019-1024
- Sugawara J, Murakami H, Maeda S, Kuno S and Matsuda M (2001) Change in post-exercise vagal reactivation with exercise training and detraining in young men. *Eur J Appl Physiol* 85: 259-263
- Swart J, Lamberts RP, Lambert MI, ST Clair Gibson A, Lambert EV, Skowno J and Noakes TD (2008) Exercising with reserve: Evidence that the CNS regulates prolonged exercise performance. *Br J Sports Med* (Epub; ahead of publ.)
- Urhausen A, Gabriel HH, Weiler B and Kindermann W (1998) Ergometric and psychological findings during overtraining: a long-term follow-up study in endurance athletes. *Int J Sports Med* 19: 114-120
- Vincent WJ (1995) *Statistics in Kinesiology*. Human Kinetics Publishers, Inc., Champaign, IL, USA.

Wilmore JH, Stanforth PR, Gagnon J, Leon AS, Rao DC, Skinner JS and Bouchard C (1996) Endurance exercise training has a minimal effect on resting heart rate: the HERITAGE Study. *Med Sci Sports Exerc* 28: 829-835

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# Chapter 7

***Measuring submaximal performance parameters to monitor fatigue and predict cycling performance: a case study of a world-class cyclo-cross cyclist. \****

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## ABSTRACT

Recently a novel submaximal test, known as the LSCT, has been developed with the purpose of monitoring and predicting changes in cycling performance. Although this test has been shown to be reliable and able to predict cycling performance, it is not known whether it can measure changes in training status. Therefore the aim of this study was to determine whether the LSCT is able to track changes in performance parameters, and objective and subjective markers of well-being. A world class cyclo-cross athlete (31 years) volunteered to participate in a 10 week observational study. Before and after the study, a peak power output (PPO) test with respiratory gas analysis ( $\text{VO}_{2\text{max}}$ ) and a 40km time trial (40km TT) test were performed. Training data was recorded in a training logbook with a daily assessment of well-being, while a weekly Lambert and Lambert Submaximal Cycle Test (LSCT) was performed. After the training period all performance parameters had improved by a meaningful amount (PPO +5.2%; 40km TT time -2.5%;  $\text{VO}_{2\text{max}}$  +1.4%). Increased training loads during weeks 2 and 6 and the subsequent training-induced fatigue was reflected in the increased well-being scores. Changes during the LSCT were most clearly notable in (i) increased power during the first minute of third stage, (ii) increased RPE during second and third stage, and (iii) a faster heart rate recovery after the third stage. In conclusion, these data suggest that the LSCT is able to track changes in training status and detect the consequences of sharp increases in training loads which seem to be associated with accumulating fatigue.

### Keywords:

LSCT • cycling • monitoring • performance • fatigue • heart rate recovery

## INTRODUCTION

There are challenges to monitoring elite cyclists to determine the optimal balance between training load and recovery so that their performance can be optimised. Regular peak performance testing, such as the peak power output test (PPO), either with or without  $\text{VO}_{2\text{max}}$ , or a 40km time trial test (40km TT) (Hawley and Noakes 1992; Jeukendrup et al. 2000; Lucia et al. 2004; Mujika and Padilla 2001; Padilla et al. 2000), are by nature exhausting and disruptive for an elite cyclist's training program. Therefore these tests are usually performed only two or three times per year (Lucia et al. 2000). This frequency of testing has limited practical value from the perspective of on-going training prescription. Although a variety of other measurement tools, such as resting heart rate ( $\text{HR}_{\text{rest}}$ ), the Profile of Mood Status questionnaire (POMS) (McNair et al. 1971), the Daily Analysis of Life Demands for Athletes questionnaire (DALDA) (Rushall 1990) and the Total Quality of Recovery scale (TQR) (Kenttä and Hassmén 1998), have been used to monitor and predict changes in training status and performance, none has been able to consistently monitor and predict changes in these parameters. A recent study by Lamberts *et al.* (2009a) proposed the use of a novel standardised submaximal cycle test, the Lamberts and Lambert submaximal cycle test (LSCT), as a monitoring tool. This test requires that a subject cycles at a fixed predetermined heart rate while a combination of power output, heart rate recovery data and a rating of perceived exertion are captured, as previously described in our paper (Lamberts et al. 2009a). The LSCT has an advantage over other submaximal cycle tests (Åstrand and Ryhming 1954; Haber et al. 1976) as there are three outcome measures which can be interpreted in context. Furthermore, the LSCT is reliable with a low typical error of measurement (TEM) and is able to detect small meaningful changes in performance (Lamberts et al. 2009a).

Therefore the aim of this study was to monitor an elite cyclist during a 10 week pre-season training period during which training load changed sharply to determine if the LSCT is able to track changes in performance parameters, and objective and subjective markers of well-being such as resting heart rate, DALDA scores and TQR scores.

## METHODS

### ***Study design***

A 31 year old Dutch cyclo-cross athlete, ranked in the top 25 in the world, volunteered to participate in this case study over 10 weeks. The cyclist was fully informed about the risks and stresses associated with the research protocol, completed a Physical Activity Readiness Questionnaire (PAR-Q) (American College of Sports Medicine 2007) and signed an informed consent form before the monitoring period started. The study was approved by the Ethics and Research Committee of the Faculty of Health Sciences of the University of Cape Town. The principles of the World Medical Association Declaration of Helsinki and the ACSM Guidelines for Use of Human Subjects were adopted in this study.

### ***Preliminary testing***

Anthropometric data including height, body mass and the sum of seven skinfolds (triceps, biceps, supra-iliac, sub-scapular, calf, thigh and abdomen) (Ross and Marfell-Jones 1991) were obtained at the start of the study. Body fat was determined as the sum of seven skinfolds and also as a percentage of body mass (Durnin and Womersley 1974). In addition, the subject was asked to maintain a similar eating pattern before each test.

### ***Performance testing***

A peak power output test, which included respiratory gas analysis ( $\text{VO}_{2\text{max}}$ ), and an endurance performance test (40km TT) were performed before and after the monitoring period. The tests were performed on a Computrainer ergometer (Computrainer Pro 3D, RacerMate, Seattle, WA, USA) using a well controlled testing protocol (Lamberts et al. 2009d). Maximal peak power output was determined as the mean power output during the final minute of the PPO test while  $\text{VO}_{2\text{max}}$  ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) was determined as the highest recorded reading for 30 seconds. The subject was asked to complete a 40km TT in the fastest possible time. No feedback was given during the trial except for completed distance. The subject was allowed to drink water *ad libitum* for the entire 40km TT.

## **LSCT**

The Lamberts and Lambert Submaximal Cycle Test (LSCT) was performed as a warm up session before each performance test, as described previously (Lamberts et al. 2009d), and on a weekly basis during the monitoring period as a warm up before a training session. The LSCT requires that a subject cycles at three predetermined heart rates eliciting 60% (6 minutes), 80 % (6 minutes) and 90% (3 minutes) of maximal heart rate ( $HR_{max}$ ). During these periods the power output, speed and cadence are captured continuously, while a rating of perceived exertion for each stage is recorded 30 seconds before the end of each stage. As the Computrainer system is recalibrated for accuracy purposes after the first stage (30 seconds) and heart rate recovery is measured during a 90 second period after the third stage, the total duration of the LSCT is 17 minutes.

## **Training load and questionnaires**

In addition to the performance tests and the weekly LSCT's, the subject was also asked to maintain a detailed daily training logbook throughout the 10 weeks. The daily Training Impulse (TRIMPS), a method to determine training load (Banister 1991), was calculated from the data collected in the logbook (mean and maximum heart rate, duration of training). Other information such as body weight, resting HR, hours of sleep per night, a rating of perceived exertion per training session and personal comments were also collected in the logbook. In addition the subject completed a DALDA questionnaire (Rushall 1990). In this questionnaire a subject responds to certain terms/feelings and indicates whether these are either '*worse than normal*' (a), '*same as normal*' (b) or '*better than normal*' (c). The DALDA is a two-part survey. In part 'A' general stressors that occur in the everyday living of the athlete are scored, while part 'B' focuses on symptoms of stressors which are likely to exist within the athlete. The number of 'a'-scores (*worse than normal*) in the 'B' section were used to determine a change in well-being of this subject, as recommended by Halson *et al.* (2002).

The subject also completed a TQR scale, which aims to measure the overall recovery process of athletes based on four recovery categories ((i) nutrition and hydration, (ii) sleep and rest, (iii) relaxation and emotional support, and (iv) stretching and active rest) (Kenttä and Hassmén 1998). Furthermore, resting heart rate was recorded each



morning 2 minutes after waking up while the subject remained in a supine position. He recorded his body mass immediately after waking up every morning using the same scale. In addition, the subject recorded the total amount of sleep per night (rounded off to 30 minutes).

### ***Data collection and analysis***

Power output, speed, cadence and elapsed time were measured during all trials and stored by the Computrainer software at a rate of 34 Hz, while a Suunto heart rate monitor (Suunto T6, Suunto Oy, Vantaa, Finland) was used to store heart rate data every 2 seconds. Oxygen uptake ( $\text{VO}_2$ ) and  $\text{CO}_2$  production ( $\text{VCO}_2$ ) were measured with an on-line breath-by-breath gas analyser and pneumotach (Oxycon Pro<sup>®</sup>, Viasis, Hoechberg, Germany) and stored as average values over 8 breaths.

Due to the slow half life of heart rate (Borresen and Lambert 2007) and the subject having to make fine adjustments to his workload to reach a specific heart rate during the warm-up, the heart rate and performance data in the first minute of each stage were excluded from analysis, as previously described (Lamberts et al. 2009a). Therefore, average power output and heart rate values were calculated over a five minute period (from minute 1.00 to 6.00 and from 7:30 to 12:30 (min:s)) for the first and second stage respectively, and for a two minute period (13:30-15.30 min:s) for the third stage of the LSCT. Heart rate recovery (HRR) was defined as the change in heart rate in the 60 seconds of recovery immediately after exercise, as previously described (Lamberts et al. 2004; Lamberts and Lambert 2009). Performance and heart rate data from the PPO test and the 40km TT test were analyzed for the full period of the data capture.

Performance data were analysed using CyclingPeaks analysis software (WKO+ edition, Version 2.1, 2006, Lafayette, CO, USA) and the Computrainer coaching software (Version 1.5.308, RacerMate, Seattle, WA, USA). Heart rate data were analysed with Suunto Training Manager (Version 2.1.0.3, Suunto Oy, Vantaa, Finland). To determine if changes in performance were substantial and meaningful, as no statistical testing could be performed ( $n=1$ ), changes in maximal performance parameters (PPO and 40km TT) and submaximal performance parameters (LSCT) were compared to their normal day-to-day variation (Lamberts et al. 2009a). The data

were analyzed graphically using a fine lowess analysis (GraphPad Prism version 3.00 for Windows, GraphPad Software, San Diego, California, USA). The day-to-day variation for each parameter (Lamberts et al. 2009a) is also plotted to provide an indication of whether the changes are meaningful and relevant.

## RESULTS

### *Performance parameters*

All performance tests were conducted under relatively stable environmental conditions (20-24 °C and 54-60% relative humidity). The PPO test and 40km TT before and after the 10 week monitoring period were separated by 3 days and conducted under the supervision of the same researcher. Changes in general characteristics and in peak and endurance performance before and after the training/monitoring period are shown in Table 7.1.

**Table 7.1** Descriptive and performance data before and after the 10 week training/monitoring period.

Variable	Test 1	Test 2	Change	% Change
<b>Descriptive data</b>				
Body mass (kg)	75.5	76.0	+ 0.5	0.7 %
Body fat percentage (%)	11.7	10.8	- 0.9	7.7 %
Sum of skinfolds (mm)	45.4	44.5	- 0.9	2.0 %
<b>Peak power output test</b>				
PPO (W)	460	484	+ 24	5.2 %
PPO (W·kg <sup>-1</sup> )	6.1	6.4	+ 0.3	4.5 %
VO <sub>2max</sub> (ml·kg <sup>-1</sup> ·min <sup>-1</sup> )	71.9	72.9	+ 1.0	1.4 %
RER <sub>max</sub>	1.16	1.19	+ 0.03	2.6 %
HR <sub>max</sub> (beats·min <sup>-1</sup> )	184	185	+ 1	0.5 %
<b>40km time trial</b>				
Time (s)	3809	3712	97	2.5 %
Average power (W)	280	300	20	7.1 %
Average speed (km·h <sup>-1</sup> )	37.8	38.8	1.1	2.6 %
Cadence (rpm)	103	102	- 1	1.0 %
Average HR (beats·min <sup>-1</sup> )	163	161	- 2	1.2 %
RPE (units)	19	19	0	0 %

The weekly LSCT's during the monitoring period were always conducted before a training session and were either performed on a Wednesday or Thursday, depending on the training schedule and racing calendar of the cyclist.

### ***Training load***

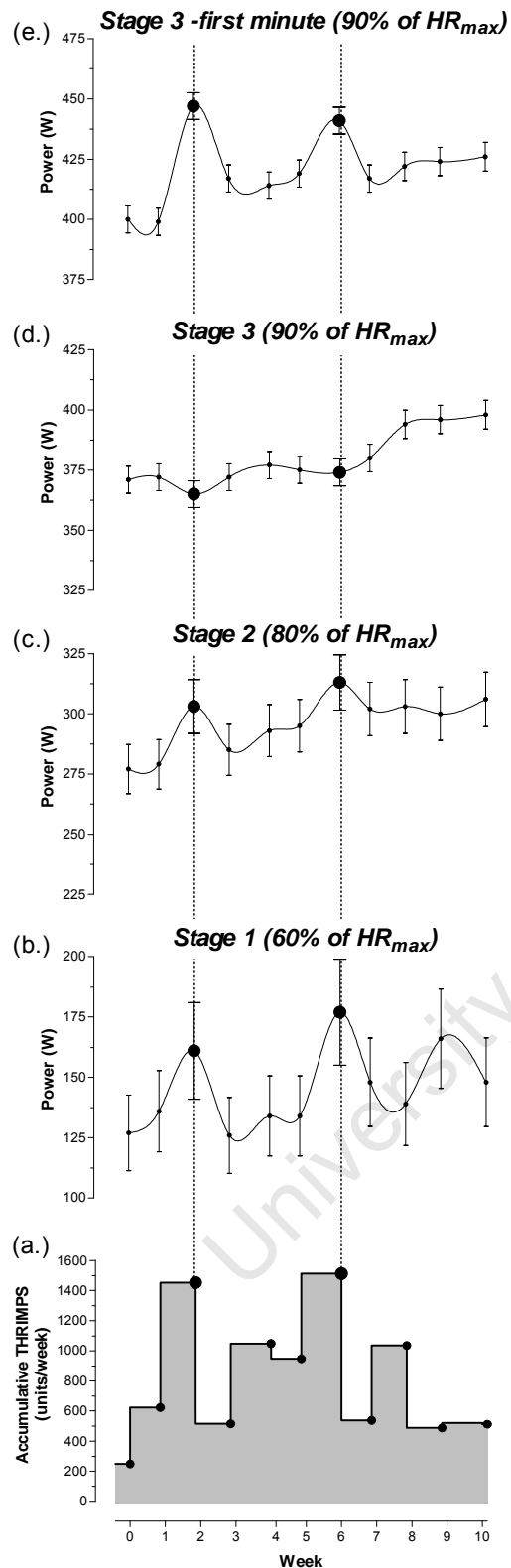
The training during the 10 week period existed of a combination of long slow distance rides, high intensity training sessions, recovery rides and resting days. Based on the type of training the cyclist performed the training duration per week fluctuated from 5 to 18 hours per week. The mean training load per week was calculated as the accumulated TRIMPS between two LSCT tests which were separated by 6 to 8 days. Based on this method a substantial increase in training load of 233% and 160% was observed during week 2 and 6, respectively.

### ***LSCT***

The subject was able to perform all the planned LSCT's and reported that the test did not interfere with his normal training or racing programme. The intensity of the 3 stages of the LSCT corresponded to  $31 \pm 4\%$ ,  $63 \pm 2\%$  and  $80 \pm 3\%$  of the subject's initial PPO respectively. Data from weeks 2 and 6 were excluded from this analysis because the training load was increased substantially during this period (Figure 7.1a). The corresponding rating of perceived exertion (RPE) with each intensity were  $8 \pm 1$ ,  $13 \pm 0$  and  $16 \pm 0$ , respectively. Mean power output within the LSCT while riding at 60%, 80% and 90% of  $HR_{max}$  is shown in Figures 7.1b, 7.1c and 7.1d respectively. Mean power during the first minute of stage 3 (riding at 90% of  $HR_{max}$ ) is shown in Figure 7.1e.

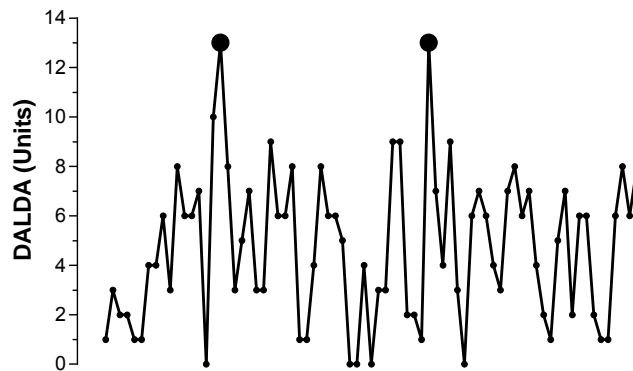
To clarify the interpretation of the data in Figure 7.1, normal day-to-day variation in power, which were determined in our companion paper (Lamberts et al. 2009a), are shown in Figure 7.1 as error bars. This display allows a visual appraisal of whether the changes were meaningful or not (Figure 7.1).

During weeks 2 and 6, coinciding with substantially higher training loads, the subject had higher power outputs during the first and second stage of the LSCT. For example power output improved during the first stage of the LSCT improved from

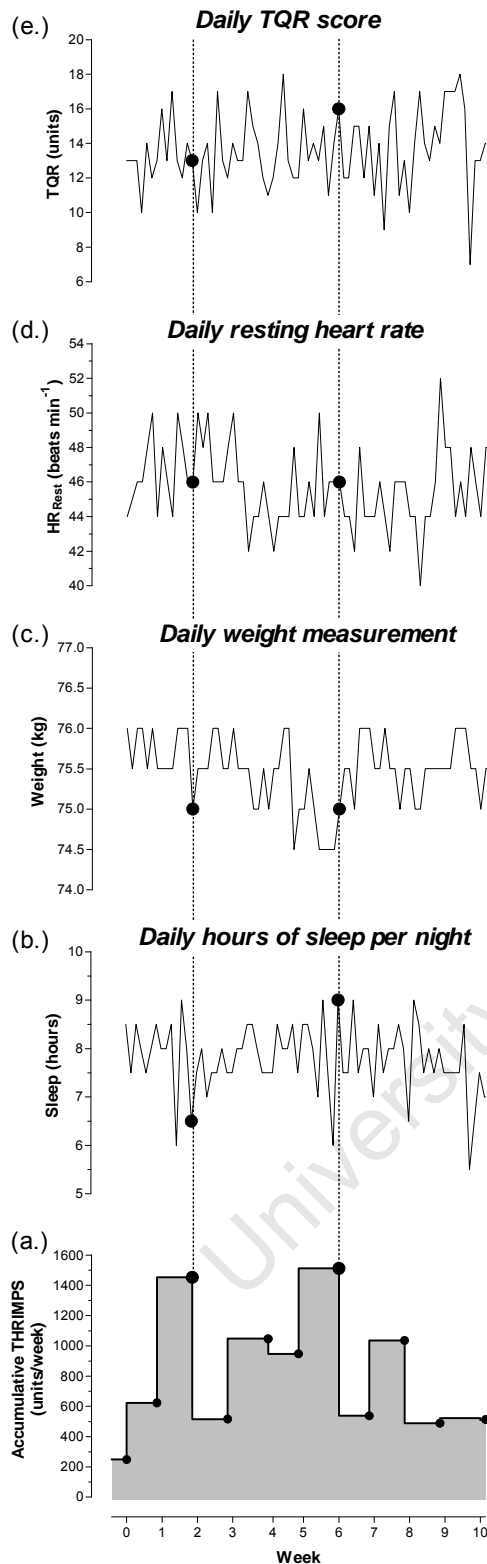


**Figure 7.1** A graphical overview of power output during the first (b), second (c) and third stage (d) and first minute of the third stage (e) of the LSCT (filled circle). The accumulative training load is shown in (a). Error bars around each LSCT indicate the normal day-to-day variations in these parameters (Lamberts *et al.* 2009a), while a lowess line was used to connect all data point. Weeks 2 and 6 are marked with a larger dot to indicate the increased training load for these weeks.

127 W to 148 W, peaking at week 2 (161 W) and 6 (177 W) and power output during the second stage improved from 277 W to 306 W, peaking at week 2 (303 W) and 6 (313 W) (see Figure 7.1b and 7.1c respectively). During the third stage, power output ranged between 371 W to 398 W, however no apparent peaks in week 2 and 6 during this stage were observed (Figure 7.1d). However, when the power output



**Figure 7.2** A graphical overview of the change in training load (a.) and other parameters which seem to have a similar pattern and responded to the increased training loads in week 2 and 6. The days when a LSCT was conducted are indicated with a dot (●). Figure 7.2b shows the daily DALDA score while Figure 7.2c and 7.2d represent the RPE of each stage of the LSCT and HRR response at the end of the LSCT, respectively. A lowless line was used in Figures c. and d. to connect the data points.



**Figure 7.3** A graphical overview of the change in training load (a.) and other parameters which do not seem to track with the changes in training load. The days when a LSCT was conducted are indicated with a dot (●). Parameters displayed are daily hours of sleep per night (b.) daily weight measurement (c.) daily resting heart rate (d.) and daily TQR score (e.).

needed to elicit 90% of  $HR_{max}$  were analysed (i.e. first minute of the third stage), two clear increases in power output during weeks 2 and 6 were observed again (Figure 7.1e).

HRR after the last stage also improved steadily from 62 beats before the training period to 71 beats at the end of the 10 weeks observational period. Two substantial peaks in HRR were observed in week 2 (69 beats) and week 6 (72 beats) of the training period (Figure 2d). The RPE's during the 3 stages of the LSCT are shown in Figure 7.2c. The RPE increased at week 2 and 6 (80 and 90% of  $HR_{max}$ ) but remained relatively unchanged at 60% of  $HR_{max}$ .

### **Questionnaires**

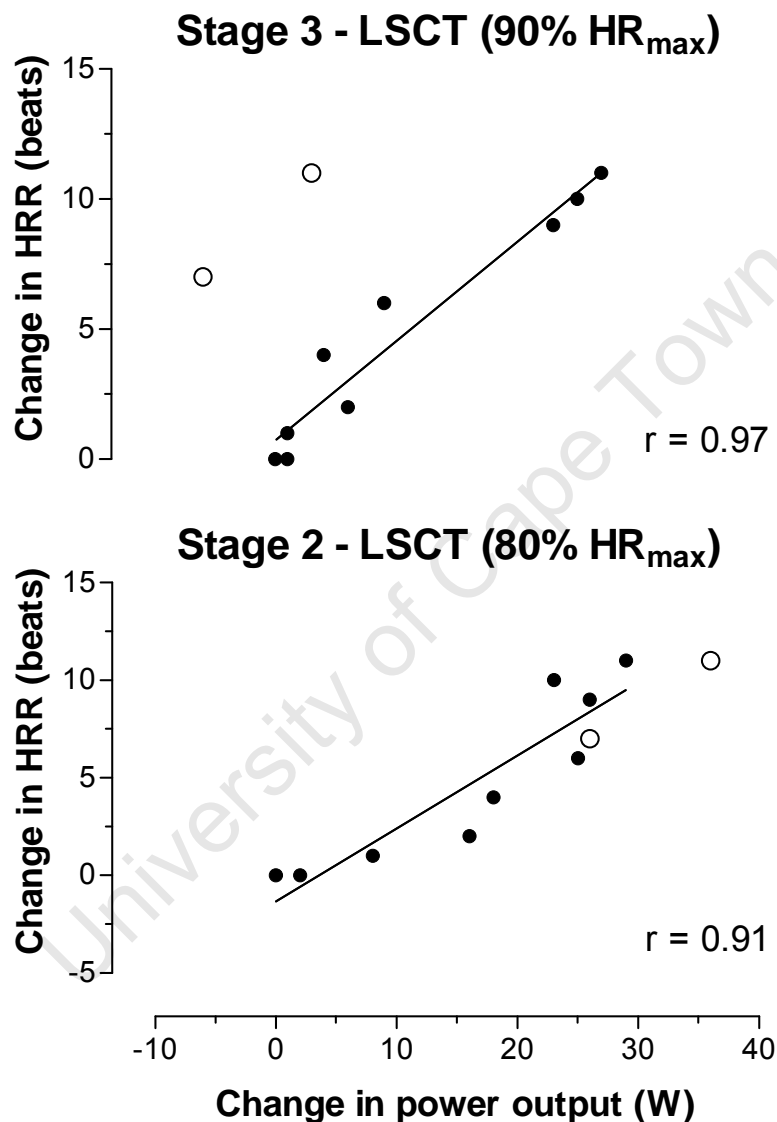
There was an increased number of 'a'-scores (i.e. "*worse than normal*") in the 'B' section of the DALDA questionnaire (Figure 7.2b) indicating increased stress levels within the athlete and a possible manifestation of symptoms of fatigue. The subject also reported higher RPE's during stage 2 and 3 of the LSCT (Figure 7.2c) and showed a much faster HRR than normal (Figure 7.2d). In contrast, the TQR questionnaire did not seem to track well with the changes in training load (Figure 7.3d).

Other parameters which did not change with training load and/or responded to the increased training load during weeks 2 and 6 are shown in Figure 3. There were no relationships between changes in training load and changes in hours of sleep per night (Figure 7.3b), body mass measured in the morning (Figure 7.3c), resting heart rate measured in the morning (Figure 7.3d) and overall TQR score (Figure 7.3e).

### **LSCT and changes in performance parameters**

The relationships between the change in HRR and change in power during the second and third stage of the LSCT were analysed. A good relationship between the change in HRR and change in power output during the second stage of the LSCT was found ( $r = 0.92$ ;  $P < 0.0001$ ). Although substantially higher power output in weeks 2 and 6 (Figure 7.1c) were noted in stage 2, excluding these data did not have a major impact on this relationship ( $r = 0.91$ ;  $P = 0.0006$ ). In contrast, a poor relationship was found between the change in HRR and the change power output

during the third stage of the LSCT ( $r = 0.63$ ;  $P = 0.0366$ ). However when the data of weeks 2 and 6 were excluded, there was a much stronger relationship between the change in HRR and change in power output ( $r = 0.97$ ;  $P < 0.0001$ ) (Figure 7.4).



**Figure 7.4** The change in HRR at the end of the LSCT and power output during second and third stage of the LSCT. Linear regression lines are drawn for both stages between change in HRR and change in power output with exclusion of the data of weeks 2 and 6 (○).

Due to the limited data points, direct correlation could not be established between the change in performance parameters measured within the LSCT and change in performance parameters measured at the start and end of the 10 week period of training. However, it is interesting to notice that the increase in power within the



LSCT (i.e. before training vs. after training) follows a similar increase in power in the PPO and 40km TT test. Mean power output during the third stage of the LSCT (27 W) improved similarly compared to the improvement in PPO (24 W) and improved slightly more than the mean power output during the 40km TT (20 W) (see also Table 7.1).

## DISCUSSION

The first finding of this study is that the subject improved his training status substantially over the 10 weeks observational training period. These improvements are similar to changes seen in professional road cyclists between 'pre' and 'in' season values (Lucia et al. 2000). Although no statistical analysis could be performed, the change in PPO and 40km TT can be regarded as meaningful for an elite cyclist because the change was more than 1% (Currell and Jeukendrup 2008; Paton and Hopkins 2001) and larger than the measured typical error of measurement (TEM) (Lamberts et al. 2009d). Although the  $\text{VO}_{2\text{max}}$  changed by more than 1%, this is within the TEM for  $\text{VO}_{2\text{max}}$ , and therefore cannot be attributed to a training effect with certainty (Lamberts et al. 2009d).

The second major finding of this study was that the improvements in PPO (24 W) and mean power during the 40km TT (20 W) were of a similar magnitude compared to the change in power output during the third stage of the LSCT (27 W). This indicates that the power output during the third stage of the LSCT, which has shown to have a good relationship with both PPO ( $r = 0.94$ ) and 40km TT power ( $r = 0.93$ ) (Lamberts et al. 2009a), is able to track changes in training status with reasonable accuracy. Furthermore, a strong relationship was found between the change in HRR and change in power output during the second and third stage off the LSCT ( $r = 0.91$  and  $r = 0.98$ ) when the data of weeks 2 and 6 were excluded from this analysis. This relationship is similar to the relationship found in a previous study in our laboratory (Lamberts et al. 2009b), between the change in 40km TT time and change in heart rate recovery after the 40km TT ( $\text{HRR}_{40\text{km}}$ ) ( $r = 0.96$ ). A study by Buchheit et al. (2008), in contrast, reported a weaker relationship ( $r = 0.62$ ) between the change in HRR and change in repeated sprint ability. However, HRR in this study (Buchheit et

al. 2008) was measured in a separate test and not directly after the repeated sprint test which may have accounted for the weaker relationship. This point is supported by the knowledge that HRR is influenced by the mode (Heffernan et al. 2006), and duration of exercise (Seiler et al. 2007) and the preceding work intensity (Kaikkonen et al. 2008).

When the data of weeks 2 and 6 were included in the analysis, a similar relationship between the change in HRR and change in power output during the second stage of the LSCT was found ( $r = 0.92$ ). However the relationship between the change in HRR and change in power output during the third stage of the LSCT decreased substantially ( $r = 0.63$ ) due to the outliers of week 2 and 6 (Figure 7.4). This finding indicates that these outliers are able to reflect the increased training load and possible accumulation of fatigue in weeks 2 and 6.

The third finding of this study was that an increase in training load, which was sufficient to change the DALDA scores, and therefore by implication reflects the manifestation of cumulative fatigue, was detected in the outcome measures of the LSCT. In particular, increased power output during the first minute of the third stage (Figure 7.1d), increased RPE levels during the second and third stage (Figure 7.2c) and a faster HRR after the third stage of the LSCT (Figure 7.2d) seemed to be the most sensitive parameters able to reflect this.

A faster HRR may seem paradoxical based on the results of early studies in this laboratory (Borresen and Lambert 2007; Lamberts et al. 2009b). However, these findings are in accordance with the work of Lehman *et al.* (1998) who reported a decrease in sympathetic intrinsic activity with the onset of fatigue, due to increased concentrations of circulating free catecholamine's. Additionally, Pichot *et al.* (2002) reported an increased parasympathetic activity in subjects who were recovering from an overload training period. Given the scenario that there was a decrease of sympathetic activity and an increase in parasympathetic activity in the subject in this study, then his HRR would have increased, as is shown in Figure 7.2d. This can be explained because HRR is a function of the interplay between sympathetic withdrawal and parasympathetic reactivation (Kannankeril et al. 2004; Pierpont and Voth 2004; Shetler et al. 2001). In the context of the results of the subject in this case

study, he would have had to work harder to elicit the same submaximal heart rates. This can be observed in the first and second stage and the first minute of the third stage in the LSCT (Figure 7.1) with increased RPE levels (Figure 7.2c).

In contrast to acute training-induced fatigue, chronic fatigue has been associated with increased sympathetic nervous activity (Baumert et al. 2006; Pichot et al. 2002) which arguably would result in a decrease in HRR. This is supported by a study which reported a decreased HRR with a blunted improvement in 40km TT performance which was attributed to cumulative fatigue associated with non-functional overreaching (Lamberts et al. 2009c). In the current case study however it seems that the subject was possibly functionally overreached. This hypothesis is based on the return of HRR and power output values during the different stages of the LSCT to the values which occurred before weeks 2 and 6, and which have shown to be good predictors of PPO and 40km TT performance (Lamberts et al. 2009a). This suggests that training-induced acute and chronic fatigue are reflected differently in the LSCT, which has important practical applications for monitoring.

In conclusion, the data of this case-study suggest that the performance parameters measured in the LSCT are able to track changes in cycling performance parameters as a consequence of changes in training load. These characteristics indicate that the LSCT has the potential to monitor changes in the training status of cyclists, and possibly can indicate the manifestation of acute fatigue before impairments in performance become more persistent. In this process it seems important that changes in power, HRR and RPE scores need to be interpreted together rather than a change in one of the parameters. Prospective studies however need to confirm these findings in a larger population.

### **ACKNOWLEDGEMENTS**

The authors would like to thank the cyclo-cross cyclist who participated in this study. This study was funded by the Medical Research Council of South Africa, Discovery Health and the University of Cape Town.

## REFERENCES

- American College of Sports Medicine (2007) Submaximal Exercise Tests. In: Whaley MH, Brubaker PH and Otto RM. (eds) ACSM's Guidelines for Exercise Testing and Prescription. Lippincott Williams & Wilkins, Baltimore, MD, USA, pp 70-74.
- Åstrand PO and Ryhming I (1954) A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during sub-maximal work. *J Appl Physiol* 7: 218-221
- Banister EW (1991) Modelling athletic performance. In: MacDougall JD, Wenger HA and Green HJ. (eds) *Physiological Testing of the High-Performance Athlete*. Human Kinetics,ampaign, IL, pp 403-425.
- Baumert M, Brechtel L, Lock J, Hermsdorf M, Wolff R, Baier V and Voss A (2006) Heart rate variability, blood pressure variability, and baroreflex sensitivity in overtrained athletes. *Clin J Sport Med* 16: 412-417
- Borresen J and Lambert MI (2007) Changes in heart rate recovery in response to acute changes in training load. *Eur J Appl Physiol* 101: 503-511
- Buchheit M, Millet GP, Parisy A, Pourchez S, Laursen PB and Ahmaidi S (2008) Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Med Sci Sports Exerc* 40: 362-371
- Currell K and Jeukendrup AE (2008) Validity, reliability and sensitivity of measures of sporting performance. *Sports Med* 38: 297-316
- Durnin JVGA and Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr* 32: 77-97

- Haber P, Schlick W, Schmid P and Mulac K (1976) Estimation of the performance spectrum of healthy adolescents by using the PWC 170 (Physical Work Capacity). *Acta Med Austriaca* 3: 164-166
- Halson SL, Bridge MW, Meeusen R, Busschaert B, Gleeson M, Jones DA and Jeukendrup AE (2002) Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* 93: 947-956
- Hawley JA and Noakes TD (1992) Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur J Appl Physiol Occup Physiol* 65: 79-83
- Heffernan KS, Kelly EE, Collier SR and Fernhall B (2006) Cardiac autonomic modulation during recovery from acute endurance versus resistance exercise. *Eur J Cardiovasc Prev Rehabil* 13: 80-86
- Jeukendrup AE, Craig NP and Hawley JA (2000) The bioenergetics of World Class Cycling. *J Sci Med Sport* 3: 414-433
- Kaikkonen P, Rusko H and Martinmaki K (2008) Post-exercise heart rate variability of endurance athletes after different high-intensity exercise interventions. *Scand J Med Sci Sports* 18: 511-519
- Kannankeril PJ, Le FK, Kadish AH and Goldberger JJ (2004) Parasympathetic effects on heart rate recovery after exercise. *J Investig Med* 52: 394-401
- Kenttä G and Hassmén P (1998) Overtraining and recovery. A conceptual model. *Sports Med* 26: 1-16

- Lamberts RP, Swart J, Noakes TD and Lambert MI (2009a) A novel submaximal cycle test (LSCT) to monitor fatigue and predict cycling performance. *Br J Sports Med* (Epub; ahead of publ.)
- Lamberts RP, Swart J, Noakes TD and Lambert MI (2009b) Changes in heart rate recovery after high-intensity training in well-trained cyclists. *Eur J Appl Physiol* 105: 705-713
- Lamberts RP, Swart J, Noakes TD and Lambert MI (2009c) Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. *Scand J Med Sci Sports*: (Epub; ahead of publ.)
- Lamberts RP, Swart J, Woolrich RW, Noakes TD and Lambert MI (2009d) Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status. *Int SportMed J* 10: 33-44
- Lehmann M, Foster C, Dickhuth HH and Gastmann U (1998) Autonomic imbalance hypothesis and overtraining syndrome. *Med Sci Sports Exerc* 30: 1140-1145
- Lucia A, Hoyos J, Perez M and Chicharro JL (2000) Heart rate and performance parameters in elite cyclists: a longitudinal study. *Med Sci Sports Exerc* 32: 1777-1782
- Lucia A, Hoyos J, Perez M, Santalla A, Earnest CP and Chicharro JL (2004) Which laboratory variable is related with time trial performance time in the Tour de France? *Br J Sports Med* 38: 636-640
- McNair DM, Lorr M and Droppleman LF (1971) *Manual for the Profile of Mood Status*. Educational and Industrial Testing Service, San Diego, CA.

- Mujika I and Padilla S (2001) Physiological and performance characteristics of male professional road cyclists. *Sports Med* 31: 479-487
- Padilla S, Mujika I, Orbananos J and Angulo F (2000) Exercise intensity during competition time trials in professional road cycling. *Med Sci Sports Exerc* 32: 850-856
- Paton CD and Hopkins WG (2001) Tests of cycling performance. *Sports Med* 31: 489-496
- Pichot V, Busso T, Roche F, Garet M, Costes F, Duverney D, Lacour JR and Barthelemy JC (2002) Autonomic adaptations to intensive and overload training periods: a laboratory study. *Med Sci Sports Exerc* 34: 1660-1666
- Pierpont GL and Voth EJ (2004) Assessing autonomic function by analysis of heart rate recovery from exercise in healthy subjects. *Am J Cardiol* 94: 64-68
- Ross WD and Marfell-Jones MJ (1991) Kinanthropometry. In: MacDougall JD, Wenger HA and Green HS. (eds) *Physiological Testing of the High Performance Athlete*. Champaign, IL: Human Kinetics, pp 223-308.
- Rushall BS (1990) A Tool for Measuring Stress Tolerance in Elite Athletes. *Journal of Applied Sport Psychology* 2: 51-66
- Seiler S, Haugen O and Kuffel E (2007) Autonomic recovery after exercise in trained athletes: intensity and duration effects. *Med Sci Sports Exerc* 39: 1366-1373
- Shetler K, Marcus R, Froelicher VF, Vora S, Kalisetti D, Prakash M, Myers J and Do D (2001) Heart rate recovery: Validation and methodologic issues. *J Am Coll Cardiol* 38: 1980-1987

# Chapter 8

## Summary and Discussion

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## INTRODUCTION

The goal of an elite athlete is to reach their potential and to be able to compete at the highest possible level in their particular sport. To achieve this goal an athlete needs to be genetically endowed for the characteristics which are important for the sport, train appropriately and have the mental capacity and perseverance to sustain this over a long period. A key feature of "training appropriately" is that the athlete needs to find the optimal balance between the training load and the amount of recovery time between training sessions. If this balance is disturbed by either a training load which is too high for the athlete to accommodate, and/or an insufficient recovery period, symptoms of fatigue will start to accumulate. Although functional overreaching and the associated training-induced fatigue may be an intentional training strategy, if the imbalance persists for prolonged periods a condition called non-functional overreaching and even an overtraining syndrome may develop. These conditions are associated with impairments in performance and may take weeks to over a year to recover from, based on the severity of the imbalance (Meeusen et al. 2006). However, as the best improvements in training status are reached by just maintaining this balance, non-functional overreaching and the development overtraining syndrome are a serious threat for the wellbeing of trained and elite cyclists.

The physiological stress of training session is defined by the duration, frequency, volume and intensity of the training session and training cycle, while the physiological stress of racing is mainly defined by the duration and intensity of the race. In both cases however, this stress is also influenced by the environmental conditions and access to nutrition before, during and after the event. The rate of recovery is influenced by more complex factors such as the true quality of the recovery period, the amount and quality of sleep, nutritional status and the psychological and sociological wellbeing of the athlete (Jeukendrup 2002; Kenttä and Hassmen 1998).

As the demand on elite cyclists is high and the best improvements in training status are achieved by a combination of a low intensity (long slow distance training (LSD) (Esteve-Lanao et al. 2007; Meyer et al. 2007; Seiler and Kjerland 2006) integrated with high intensity training (HIT) (Laursen et al. 2002; Laursen and Jenkins 2002;

Stepto et al. 1999), the minimal but yet adequate recovery periods can easily lead to a disturbed balance between training load and recovery.

The training status of a cyclist can be assessed by establishing their performance capacity during either a maximal or high effort submaximal test (i.e. the peak power output test and a 40-km time trial, respectively). However, as both these tests are physically demanding, they may therefore interfere with the cyclist's normal training programme and/or racing schedule. As a result these performance tests are normally performed only twice or three times per year (Lucia et al. 2000), with the consequence that they are not suitable for monitoring changes in training status on a regular basis. However as small differences in training status can make the difference between winning and losing, the demand for a submaximal test which can be performed on a regular basis and can monitor the accumulation of fatigue and changes in performance parameters has grown.

*Therefore the aim of this thesis was to develop a submaximal test which is able to monitor the accumulation of fatigue and predict changes in performance parameters.*

To assure the practical applicability of this test in an elite cycling environment, the test, Lamberts and Lambert Submaximal Cycle Test (LSCT), had to fulfil the following characteristics:

- should be non-invasive and submaximal
- should not interfere with the subject's normal training or racing habits
- should be suitable to use as a warming up session before a performance test, training session, or racing event
- have a maximal duration of a 'normal' warming up period (about 20 minutes)
- should be able to measure both objective and subjective data simultaneously
- have sufficient sensitivity to be able to reflect meaningful changes in performance parameters

The overall aim was to develop a test which would be able to monitor the accumulation of fatigue and predict changes in performance parameters. To accomplish this goal 6 studies were designed to provide evidenced-based support for the LSCT. The main findings of these studies are summarised below.

## SUMMARY AND CONCLUSIONS OF THE RESEARCH STUDIES

### Study 1

#### ***Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training***

This study was conducted to determine the exercise intensity which elicited the lowest variation in submaximal heart rate heart rate recovery (HRR). This study showed that the lowest day-to-day variation in HRR occurred with exercise at an intensity either between 85 and 90% of maximum heart rate ( $HR_{max}$ ) or more than 95% of  $HR_{max}$ . As a result of these findings, the LSCT was designed to include exercise at an intensity of 85 and 90% of  $HR_{max}$  with the goal of achieving the lowest possible day-to-day variation in HR and HRR as this would be an important factor in determining a precise test with the ability to detect small but meaningful changes.

This study also showed that subjects who tended to train more and therefore have a better training status, elicited lower percentages of  $HR_{max}$  during the LCST test. This introduced a possible confounding factor as it suggested that the measurement of recovery heart rate could be affected by the percentage of  $HR_{max}$  at the end of the test. As HRR has an exponential decay over time, recovering from a bout of exercise which elicited a different maximal heart rate might make the interpretation of changes in HRR more difficult. This factor was considered when the LSCT was designed. Therefore it was decided to address this problem by fixing heart rate rather than power output (W) as a marker of exercise intensity. This decision also enabled the measurement of changes in power output at different submaximal levels through a period of monitoring training. The low day-to-day variation in heart rate and heart rate recovery within the HIMS assisted in selecting the intensity of the final stage (90% of  $HR_{max}$ ) of the LSCT.

## Study 2

### ***Changes in heart rate recovery after high intensity training in well-trained cyclists***

The aim of this study was to determine whether HRR also changed with a change in training status in already well-trained cyclists. Although several studies have shown that HRR is faster in physically active people compared to sedentary people (Bunc et al. 1988; Short and Sedlock 1997) and HRR changes with an improvement in training status in already physically active adolescents (Buchheit et al. 2008), it was not known whether the same changes in HRR also occurs in already well-trained subjects.

The findings of this study showed that HRR, which was measured after a 40km time trial ( $HRR_{40km}$ ), also improved in already well-trained cyclists after a 4 week period of high intensity training (HIT) which had improved their training status. A strong relationship ( $r = 0.97$ ) between the change in 40km TT time and the change in  $HRR_{40km}$  was found. This relationship was much stronger than the reported relationship ( $r = 0.62$ ) between the change in sprint ability and the change in HRR which was measured in another study (Buchheit et al. 2008). Although the higher relationship could possibly be attributed to fact that the improvement in 40km TT time and change in HRR was measured within the same test, compared to the study of Buchheit *et al* 2008) where HRR and sprint ability were measured on different occasions, the practical value of this measurement is very limited as the 40km TT time is already known when  $HRR_{40km}$  is measured.

However, the findings of this study confirm that HRR also changes with a change in training status in already well-trained cyclists, and therefore could be a valuable parameter to measure within LSCT.

### Study 3

#### ***Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters.***

The aim of this study was to monitor the relationship between HRR after exercise and cycling performance in a group of well-trained cyclists who participated in a 4 week high intensity training program (HIT) program.

In addition to HRR which was measured after the 40km TT ( $HRR_{40km}$ ), as described in study 2, HRR during this study was also measured after each HIT session ( $HRR_{HIT}$ ). After the study subjects were retrospectively assigned to either a group which showed a continuous increase in  $HRR_{HIT}$  ( $G_{Incr}$ ) (faster;  $n = 8$ ) or a group that showed a decrease in  $HRR_{HIT}$  ( $G_{Decr}$ ) (slower;  $n = 6$ ) during the HIT period.

The analysis showed that  $G_{Decr}$  was relatively younger, had a lower body weight and body fat percentage and were better trained than  $G_{Incr}$ . However, even when changes in performance were expressed as relative change (percentage of initial measurement), mean power output during the 40km TT improved significantly more in  $G_{Incr}$ . This also resulted in a trend for 40km TT time having improved more in  $G_{Incr}$ , while no differences in improvement were found in PPO and  $VO_{2max}$ .

This study shows that HRR can potentially indicate the accumulation of fatigue which initially seems to impair endurance performance (40km TT) rather than peak performance (PPO).

#### Study 4

##### ***Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status.***

The aim of this study was to determine the typical error of measurement of different laboratory tests for the prediction of performance, including the peak power output (PPO) test and the 40-km time trial (40km TT), within a group of well-trained cyclists who maintained a constant training status.

The typical error of measurement (TEM) in performance tests conducted in the general population is about 2-3% (Paton and Hopkins 2001), while a change in performance parameters of 1% in elite cyclists should be regarded as a meaningful difference (Currell and Jeukendrup 2008; Paton and Hopkins 2006). Based on the magnitude of these data it may be concluded that it would not be practical to measure small meaningful changes in the training status of well-trained cyclist. However, the TEM of 2-3% was derived from the general population and therefore the data may not be transferable to well-trained cyclists particularly as they are likely to perform tests with more repeatability because of their experience and ability to adopt a similar pacing strategy between trials.

The findings of the study showed that with the use of a well controlled, standardised warm-up/ testing protocol (LSCT), the TEM in a PPO test could be reduced to 0.9% for PPO, 2.2% for  $VO_{2max}$ , and 0.7% for the 40km TT time trial. Based on these findings we concluded that there would be sufficient precision to track small meaningful changes over time in both the PPO and 40km TT time. In contrast, the TEM in the measurement of  $VO_{2max}$  is too high for monitoring small meaningful changes over time.

## Study 5

### ***A novel submaximal test to monitor and predict cycling performance.***

The aim of this study was to determine firstly the reliability of parameters measured during a novel submaximal cycle protocol (LSCT) and secondly how these values could predict, peak power and endurance cycling performance in well-trained cyclists.

As these data were analysed together with the data of study 5, we were able to test the reliability of the LSCT over 6 occasions. The parameters measured within the LSCT were then correlated to the mean PPO and 40km TT performance, which after familiarisation were each performed 3 times. The study showed that LSCT was truly submaximal and subjects were able to maintain their heart rate close to their target heart rates. Furthermore, the test did not interfere with their normal training habits. The LSCT was reliable and associated with a relatively low typical error of measurement (TEM) for each parameter. The lowest TEMs were found for mean power and speed during the third stage of the LSCT. The measurement of HRR was also reliable and smaller than what has been measured as a result of an improved training status (Buchheit et al. 2008; Lamberts et al. 2009c; Sugawara et al. 2001). Good relationships between the mean power of the third stage of the LSCT and PPO and 40km TT performance parameters were also found ( $r = 0.91-0.94$ ). In contrast to power, HRR showed a weaker relationship to PPO and 40km TT performance and possibly is a stronger indicator of accumulating fatigue (see study 3).

In conclusion, the LSCT is a reliable test which is able to predict cycling performance parameters from submaximal power, RPE and HRR in well-trained cyclists. As these parameters are able to detect meaningful changes, the LSCT has the potential to monitor cycling performance with more precision than other current existing submaximal cycle protocols.



## Study 6

### ***Measuring submaximal performance parameters to monitor fatigue and predict cycling performance: a case study of a world-class cyclo-cross cyclist.***

This study monitored an elite cyclist during a 10 week pre-season training period during which his training load changed sharply. The aim of the study was to determine whether the LSCT is able to track changes in performance parameters, and objective and subjective markers of well-being such as resting heart rate, Daily Analysis of Life Demands for Athletes (DALDA) scores and Total Quality of Recovery (TQR) scores.

In this study we monitored a 32 year old Dutch cyclo-cross cyclist, ranked in the top 25 in the world, during 10 weeks of preseason training. Before and after this period the subject performed a PPO and 40km TT, while the subject performed a LSCT on a weekly basis. Additionally, the subject maintained a full training logbook which captured data about his training load, daily body weight, hours of sleep and TQR score. In addition to this, the subjects also completed the DALDA every day. During the monitoring period the subject had an increase in training load during week 2 and 6, of 233% and 160% respectively.

This study showed that the small, but meaningful improvement in power output during the third stage of the LSCT (27 W) was similar to the improvements in PPO (24 W) and 40km TT (20 W) after the training period. Additionally, a strong relationship was found between the change in HRR and change in power output during the third stage off the LSCT ( $r = 0.98$ ) when the data of weeks 2 and 6 were excluded from this analysis. However when weeks 2 and 6 were not excluded, the relationship decreased substantially ( $r = 0.63$ ) due to these outliers. Another finding of this study was that an increase in training load, which was also sufficient to change the DALDA scores, and therefore by implication reflects the manifestation of cumulative fatigue, was detected in the outcome measures of the LSCT. In particular, increased power output during the first minute of the third stage, increased RPE levels during the second and third stage and a faster HRR after third stage of the LSCT seemed to be the most sensitive parameters able to reflect this. Although the faster HRR seem to be in conflict with the findings of study 3, these are supported by

the work of Lehman *et al.* (1998) and Pichot *et al.* (2002).

In contrast to acute training-induced fatigue which seems to result in a faster HRR, chronic fatigue seems to be associated with increased sympathetic nervous activity (Baumert *et al.* 2006; Pichot *et al.* 2002) and would result in a decrease in HRR. This is supported by the data from study 3 in which subjects showed a decrease in HRR on 2 consecutive occasions, where an increased HRR was seen after 1 week with an intensified training load and after which HRR returned to more normal values.

In conclusion, this case study indicates the potential of the LSCT to monitor fatigue and predict changes in performance parameters. However further research in a larger population is needed to confirm these findings.

In the next section the collective findings of these studies are combined into a model designed to monitor cyclists.

## PROPOSED MODEL USING THE LSCT TO MONITOR FATIGUE AND CHANGES IN PERFORMANCE

A hypothetical model on how the LSCT reflects a change in training status and how measurements during the LSCT respond to acute and the chronic accumulation of fatigue is discussed below. This hypothetical model has been formulated based on the findings of the 6 studies of this thesis and the general principles of exercise physiology (Brooks et al. 2005).

Meaningful changes measured by the LSCT are defined by values which are higher than the normal day-to-day variation of those variables. These are shown in Table 8.1.

**Table 8.1** An overview of meaningful changes of parameters measured by the LSCT.

	Meaningful difference (absolute value)*	Meaningful difference (Relative value)*
<b>Stage 1</b>		
Power	$\geq 18 \text{ W}$	$\geq 16\%$
Speed	$\geq 3 \text{ km}\cdot\text{h}^{-1}$	$\geq 8\%$
Cadence	$\geq 7 \text{ rpm}$	$\geq 7\%$
RPE	$\geq 2.0 \text{ units}$	-
<b>Stage 2</b>		
Power (W)	$\geq 11 \text{ W}$	$\geq 6\%$
Speed ( $\text{km}\cdot\text{h}^{-1}$ )	$\geq 2 \text{ km}\cdot\text{h}^{-1}$	$\geq 3\%$
Cadence (rpm)	$\geq 6 \text{ rpm}$	$\geq 7\%$
RPE (units)	$\geq 2.0 \text{ units}$	-
<b>Stage 3</b>		
Power (W)	$\geq 6 \text{ W}$	$\geq 3\%$
Speed ( $\text{km}\cdot\text{h}^{-1}$ )	$\geq 2 \text{ km}\cdot\text{h}^{-1}$	$\geq 3\%$
Cadence (rpm)	$\geq 6 \text{ rpm}$	$\geq 6\%$
RPE (units)	$\geq 2.0 \text{ units}$	-
<b>Recovery</b>		
HRR	$\geq 3 \text{ beats}$	$\geq 6\%$

\* Values are based on the study 5 (Lamberts et al. 2009b)

### **Changes in measurements during the LSCT with changes in training status**

The maximal heart rate and submaximal heart rate at high intensities remains relatively unchanged in professional cyclists throughout the season (Lucia et al. 2000), providing they do not become fatigued or overtrained. Based on the knowledge that peak power and submaximal power improves with an improvement in training status, and decreases with a decrease in training status (Brooks et al. 2005; Jeukendrup 2002), we expect that these changes also can be seen within the LSCT. Support for this hypothesis was found in Chapter 7, in which a cyclo-cross cyclist showed a similar improvement in PPO (24 W) and power output at 90% of  $HR_{max}$  (27 W) within the LSCT (Lamberts et al. 2009a). Additional support for this hypothesis was found in Chapter 6, in which a good correlation ( $r = 0.94$ ) was found between PPO and power output at 90% of  $HR_{max}$  (Lamberts et al. 2009b). However, as Chapter 6 did not study whether a change in PPO is reflected in a change power output at 90% of  $HR_{max}$  and Chapter 7 describes a case study, future research needs to confirm this hypothesis.

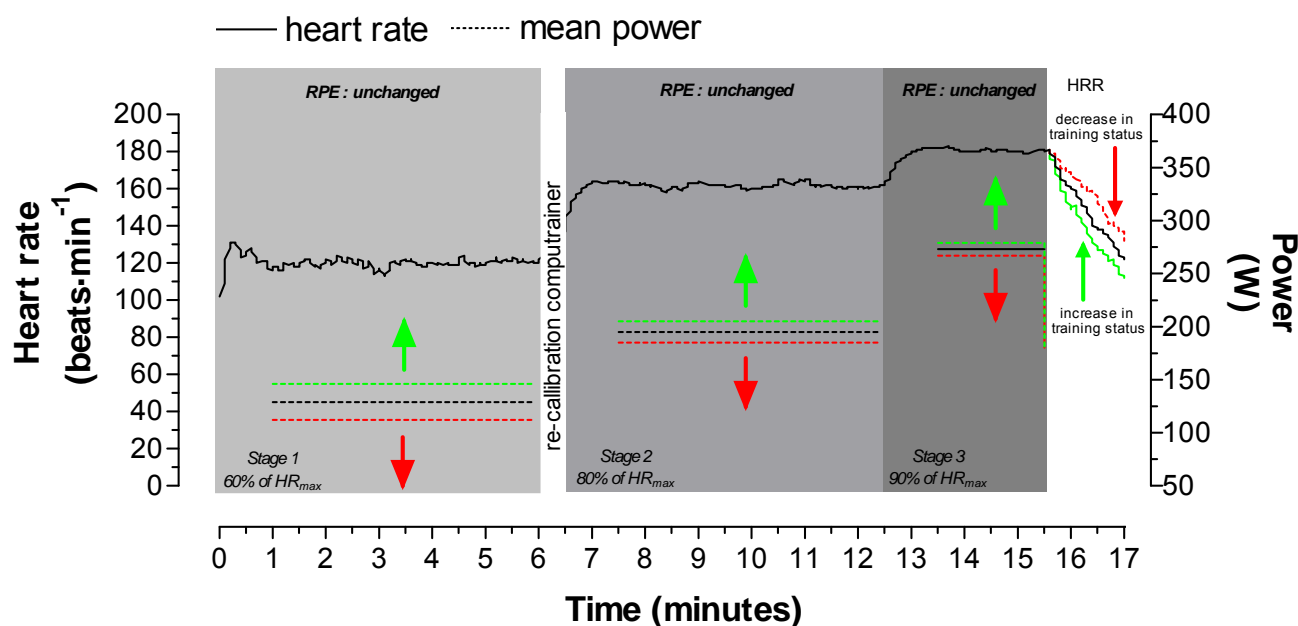
Hypothetically, assuming that submaximal power output changes with a change in training status, we expect this is reflected in the LSCT as follows (see also figure 8.1):

#### *Improved training status:*

- Higher power output especially during the second ( $\geq 6\%$  or  $\geq 11W$ ) and third stage ( $\geq 3\%$  or  $\geq 6 W$ ) of the LSCT
- A faster HRR ( $\geq 6\%$  or  $\geq 3$  beats) after the third stage of the LSCT
- The same or similar RPE scores (within 1 unit).

#### *Decrease in training status:*

- Lower power output especially during second ( $\geq 6\%$  or  $\geq 11W$ ) and third stage ( $\geq 3\%$  or  $\geq 6 W$ ) of the LSCT
- A slower HRR ( $\geq 6\%$  or 3 beats) after the third stage of the LSCT
- The same or similar RPE scores (within 1 unit).



**Figure 8.1** Graphical presentation of meaningful changes in power (W) and HRR response with either an improvement in training status (green arrows) or a decrease in training status (red arrows).

\* The green and red dotted line during the first, second and third stage of the LSCT are represented by the TEM (Table 8.1) in the power measurement during these stages.

### Changes in LSCT with fatigue

As peak and submaximal power decreases with the accumulation of fatigue (Halsen et al. 2002; Urhausen et al. 1998), it has been suggested that RPE levels increase with fatigue (Rietjens et al. 2005; Uusitalo et al. 1998) and HRR tracks with changes in training status (Sugawara et al. 2001). Therefore, the LSCT can possibly monitor the accumulating fatigue and possibly even assist with identifying a state of functional or non-functional overreaching. Although it is likely that additional tests such as a clinical assessment and a double maximum exertion test as described by Meeusen et al (2004) are needed to confirm a state of overreaching or overtraining, the LSCT seems to be a more practical tool for monitoring fatigue on a regular basis without interfering with their normal training habits.

The hypothetical responses to acute and chronic fatigue are discussed below.

### Changes in the LSCT with the accumulation of acute fatigue.

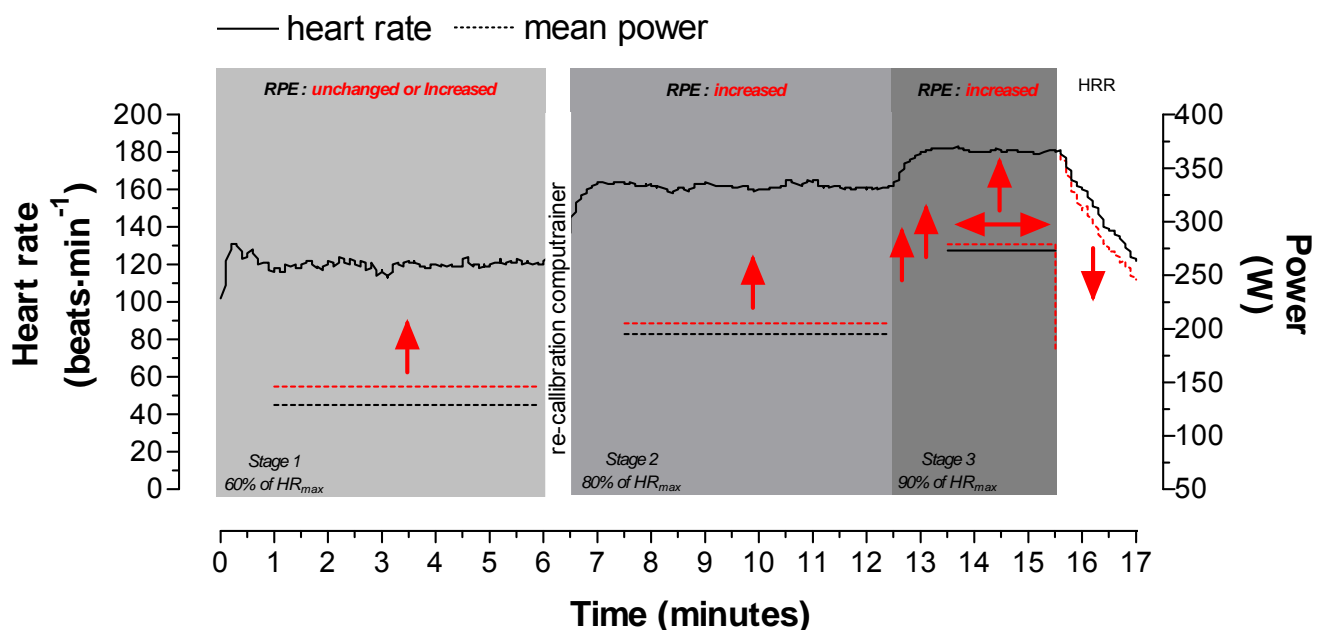
In Chapter 7 a decrease in power output was seen at 60 and 80% of  $HR_{max}$ , while a stagnation in power output was seen at 90% of  $HR_{max}$  on two occasions. These decrements in performance were seen with an increased rating of perceived exertion

and an increased heart rate recovery, which could reflect the accumulation of fatigue. However, the subject decreased his training load substantially in the following week, possibly allowing his body to recover and therefore power output, RPE and HRR returned to 'normal' values. As such a response shows similarities with a state of functional overreaching (Meeusen et al 2004), it is possible the observed responses within the LSCT are able to reflect this status. However as this was only a case study we want to emphasize that this is a hypothetical model which needs to be tested and confirmed in future research projects. However we hypothesize that the following adaptations will be seen within the LSCT with the accumulation of acute fatigue (see also Figure 8.2):

- Higher power outputs especially during second ( $\geq 6\%$  or  $\geq 11\text{W}$ ) and first minute of third stage of the LSCT ( $\geq 3\%$  or  $\geq 7\text{ W}^*$ ).

\* Unpublished data. Repeatability power measurement from the first minute of the third stage: ICC = 1.00 (90% CI= 0.98 - 1.00) , TEM = 5.5 (90% CI: 4.8 - 6.4) and TEM% 1.7 (90% CI: 1.5 - 2.0).

- A faster HRR ( $\geq 6\%$  or  $\geq 3$  beats) after stage 3 of the LSCT.
- Increased RPE ( $\geq 2.0$  units) during the second and third stage of the LSCT.
- Possibly not being able to reach the target HR of the third stage of the LSCT.

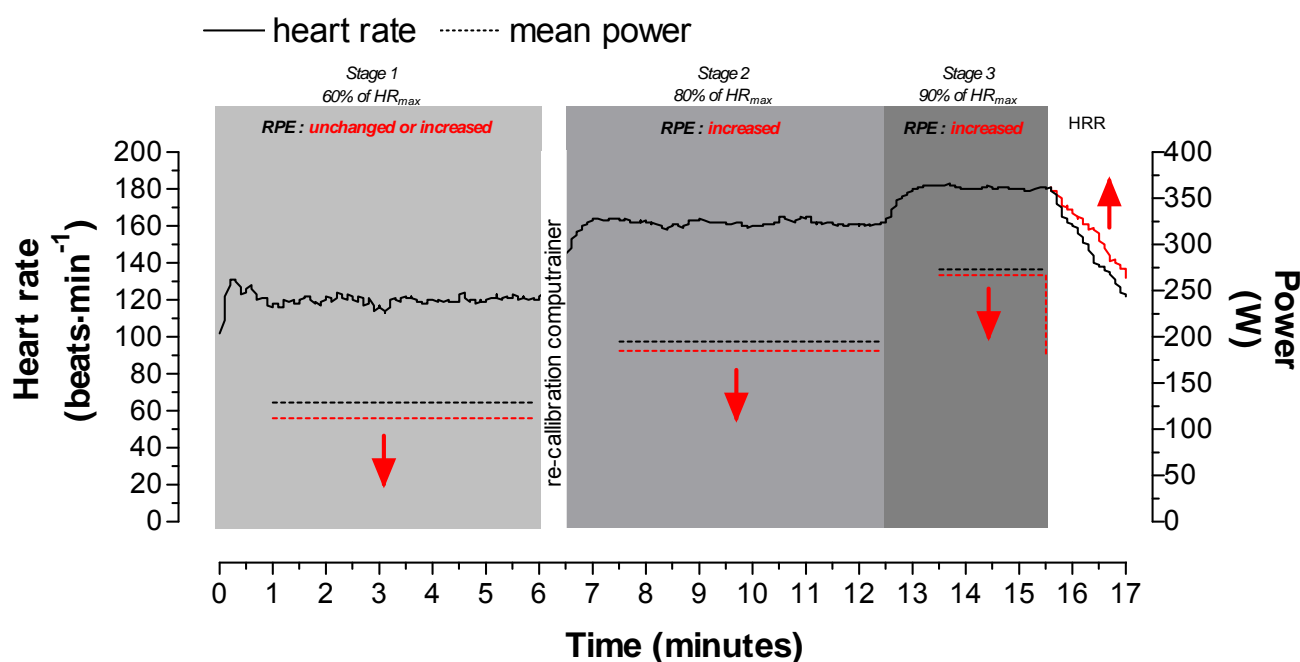


**Figure 8.2** Graphical presentation of the responses from the LSCT to acute fatigue or possibly non-functional state of overreaching.

### Changes in the LSCT with the manifestation of chronic fatigue.

If the balance between training load and recovery persists the accumulation of fatigue becomes chronic and the decrement in performance progresses. Urhausen et al (1998) showed that endurance performance is initially affected while no changes in 10 and 30 second sprints were seen. This is in line with the blunted improvements in 40km TT power we documented in  $G_{Decr}$  in Chapter 4. Although there were no real decreases in 40km TT power in  $G_{Decr}$ ,  $G_{Incr.}$  improved significantly more in then  $G_{Incr.}$ . This blunted improvement could indicate the start of a stagnation or even a decrease in endurance performance in  $G_{Decr}$ . This is supported by the decrease in HRR which has been associated with a decrease in training status (Sugawara et al. 2001). According to this explanation, we expect to see the following changes within the LSCT with the chronic manifestation of fatigue (see also Figure 8.3):

- Lower power outputs especially during the second ( $\geq 6\%$  or  $\geq 11W$ ) and third stage ( $\geq 3\%$  or  $\geq 7 W$ ) of the LSCT.
- A slower HRR ( $\leq 6\%$  or  $\leq 3$  beats) after stage 3 of the LSCT.
- Increased RPE levels ( $\geq 2.0$  units) during the second and third stage of the LSCT.



**Figure 8.3** Proposed hypothesis on how the LSCT would reflect a state of chronic fatigue or possibly a non-functional state of overreaching.

\* The scenario of not being able to reach the target heart rate during the third stage of the LSCT is not graphically displayed.

## CONCLUSION

Based on the findings of the different studies within this thesis and research which is in accordance with other research findings (Brooks et al. 2005; Buchheit et al. 2007b; Buchheit et al. 2007a; Buchheit et al. 2008; Halson et al. 2002; Halson and Jeukendrup 2004; Jeukendrup 2002; Lehmann et al. 1998; Lehmann et al. 1997; Meeusen et al. 2004; Rietjens et al. 2005; Rushall 1990; Sugawara et al. 2001; Uusitalo et al. 1998), we conclude that the LSCT has the potential to monitor changes in training status on a regular basis. However, it seems highly unlikely that only one parameter can consistently and accurately indicate acute fatigue or predict the accumulation of fatigue. Therefore we find it prudent to suggest that rather than focus on a single predictor, a combination of parameters should be used to monitor changes in training status and to predict the accumulation of fatigue. In particular the combination of an objective data source (i.e. measurement of power), an subjective data source (i.e. rating of perceived exertion) and alterations in the functioning of the autonomic nervous system (measured by HRR) shows advantages over measuring and interpreting just one variable. However, future research needs to determine which combination of these parameters reflects particular changes in training status and/or indicates the accumulation of fatigue.

In conclusion, the LSCT shows potential to monitor and predict changes in training status and possibly can play an important role in reflecting fatigue levels. This can have important practical implications for scientists and coaches who can use this information to optimize training programs and diagnose states of non-functional and functional overreaching at an early stage.

In an attempt to assist with decision-making and the interpretation of data measured during the LSCT, a scheme is proposed in Table 8.2. This scheme is hypothetical based on the data presented in this thesis. Further research needs to test the accuracy and practical application of the model.



**Table 8.2** A scheme to describe the decision-making of adjusting training load ,based on the change in performance parameters measured within the LSCT

Amount of changes within LSCT parameters	Description	Examples <sup>#</sup>	Recommendation
0	No changes one of the LSCT parameters in HRR, power output and RPE.	<ul style="list-style-type: none"> <li>• No change in HRR, power outputs* and RPE levels**</li> </ul>	<p>No indication of accumulation of fatigue.</p> <p><b>Keep on training</b></p>
1	Change in <u>one</u> of the LSCT parameters HRR, power output or RPE	<ul style="list-style-type: none"> <li>• A faster HRR with no change in power outputs* and RPE levels**</li> <li>• Change in RPE levels** scores without a change in power outputs* and HRR</li> <li>• Change in power outputs* without a change in HRR and RPE levels**</li> </ul>	<p>Unlikely risk for the accumulation of fatigue</p> <p>No direct indication for the accumulation of fatigue.</p> <p><b>Carefully monitor symptoms</b></p>
2	Change in <u>two</u> of the LSCT parameters HRR, power output or RPE	<ul style="list-style-type: none"> <li>• A faster HRR with an increase power output* but no change in RPE levels**</li> <li>• A slower HRR with increased RPE levels** but no change in power output*</li> <li>• A slower HRR with decrease in power outputs but no change in RPE levels</li> </ul>	<p>Likely risk for the accumulation of fatigue</p> <p><b>Adapt training protocol and monitor symptoms.</b></p> <p><i>(lower training load and/or increase recovery period)</i></p>
3	Change in <u>all</u> of the LSCT parameters HRR, power output and RPE	<ul style="list-style-type: none"> <li>• A slower HRR with increased RPE levels and a decrease in power output</li> <li>• A faster HRR with an increase in power during the first minute of the third stage and increased RPE levels.</li> </ul>	<p>Highly likely risk of the accumulation of fatigue with detrimental effects on performance.</p> <p><b>Adapt training protocol !!</b></p> <p><i>(minimize training load or increase recovery time)</i></p>

<sup>#</sup> These are examples, not all possible scenarios are given

\* Meaningful change in power output during stage 2 and 3 and the first minute of the stage 3.

\*\* Meaningful change in RPE during stage 2 and 3.

### **Proposed research studies for the future.**

Although this thesis has formed the basis for a novel submaximal cycle test designed to monitor training status and predict performance on a regular basis, further research is needed to confirm the capabilities of the LSCT and test the theoretical model which has been proposed above.

Although heart rate recovery (HRR), was selected as one of the main outcome measures, based on the papers of Buchheit et al. (2007b; 2008), the measurement of heart rate variability (HRV) also shows the potential of being a useful marker in monitoring fatigue and changes in training status. However, as there is no consensus on how to analyse HRV data, judgements about the practical value of HRV analysis seem to be premature and difficult to make at this stage. However when consensus is reached on how to analyse HRV data, this information can possibly be added as a valuable extra component to the LSCT.

## REFERENCES

- Baumert M, Brechtel L, Lock J, Hermsdorf M, Wolff R, Baier V and Voss A (2006) Heart rate variability, blood pressure variability, and baroreflex sensitivity in overtrained athletes. *Clin J Sport Med* 16: 412-417
- Brooks GD, Fahey TD and Baldwin KM (2005) *Exercise Physiology: Human Bioenergetics and Its Applications*. McGraw-Hill, New York, NY.
- Buchheit M, Laursen PB and Ahmaidi S (2007a) Parasympathetic reactivation after repeated sprint exercise. *Am J Physiol Heart Circ Physiol* 293: H133-H141
- Buchheit M, Millet GP, Parisy A, Pourchez S, Laursen PB and Ahmaidi S (2008) Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Med Sci Sports Exerc* 40: 362-371
- Buchheit M, Papelier Y, Laursen PB and Ahmaidi S (2007b) Noninvasive assessment of cardiac parasympathetic function: postexercise heart rate recovery or heart rate variability? *Am J Physiol Heart Circ Physiol* 293: H8-H10
- Bunc V, Heller J and Leso J (1988) Kinetics of heart rate responses to exercise. *J Sports Sci* 6: 39-48
- Currell K and Jeukendrup AE (2008) Validity, reliability and sensitivity of measures of sporting performance. *Sports Med* 38: 297-316
- Esteve-Lanao J, Foster C, Seiler S and Lucia A (2007) Impact of training intensity distribution on performance in endurance athletes. *J Strength Cond Res* 21: 943-949
- Halsen SL, Bridge MW, Meeusen R, Busschaert B, Gleeson M, Jones DA and Jeukendrup AE (2002) Time course of performance changes and

fatigue markers during intensified training in trained cyclists. J Appl Physiol 93: 947-956

Halsen SL and Jeukendrup AE (2004) Does overtraining exist? An analysis of overreaching and overtraining research. Sports Med 34: 967-981

Jeukendrup A (2002) High-performance cycling. Human Kinetics Publishers, Inc., Champaign, IL, USA.

Kenttä G and Hassmen P (1998) Overtraining and recovery. A conceptual model. Sports Med 26: 1-16

Lamberts RP, Rietjens G.J., Tjondink HH, Noakes TD and Lambert MI (2009a) Measuring submaximal performance parameters to monitor fatigue and predict cycling performance: a case study of a world-class cyclo-cross cyclist. Eur J Appl Physiol Epub; ahead of publication.

Lamberts RP, Swart J, Noakes TD and Lambert MI (2009b) A novel submaximal cycle test to monitor fatigue and predict cycling performance. Br J Sports Med Epub; ahead of publication.

Lamberts RP, Swart J, Noakes TD and Lambert MI (2009c) Changes in heart rate recovery after high-intensity training in well-trained cyclists. Eur J Appl Physiol 105: 705-713

Lamberts RP, Swart J, Noakes TD and Lambert MI (2009d) Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. Scand J Med Sci Sports Epub; ahead of publication.

Laursen PB and Jenkins DG (2002) The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. Sports Med 32: 53-73

- Laursen PB, Shing CM, Peake JM, Coombes JS and Jenkins DG (2002) Interval training program optimization in highly trained endurance cyclists. *Med Sci Sports Exerc* 34: 1801-1807
- Lehmann M, Foster C, Dickhuth HH and Gastmann U (1998) Autonomic imbalance hypothesis and overtraining syndrome. *Med Sci Sports Exerc* 30: 1140-1145
- Lehmann MJ, Lormes W, Opitz-Gress A, Steinacker JM, Netzer N, Foster C and Gastmann U (1997) Training and overtraining: an overview and experimental results in endurance sports. *J Sports Med Phys Fitness* 37: 7-17
- Lucia A, Hoyos J, Perez M and Chicharro JL (2000) Heart rate and performance parameters in elite cyclists: a longitudinal study. *Med Sci Sports Exerc* 32: 1777-1782
- Meeusen R, Duclos M, Gleeson M, Rietjens GJ, Steinacker JM and Urhausen A (2006) Prevention, diagnosis and treatment of the overtraining syndrome. *Eur J Sport Sci* 6: 1-14
- Meeusen R, Piacentini MF, Busschaert B, Buyse L, De Schutter G and Stray-Gundersen J (2004) Hormonal responses in athletes: the use of a two bout exercise protocol to detect subtle differences in (over)training status. *Eur J Appl Physiol* 91: 140-146
- Meyer T, Auracher M, Heeg K, Urhausen A and Kindermann W (2007) Effectiveness of low-intensity endurance training. *Int J Sports Med* 28: 33-39
- Paton CD and Hopkins WG (2001) Tests of cycling performance. *Sports Med* 31: 489-496
- Paton CD and Hopkins WG (2006) Ergometer error and biological variation in power output in a performance test with three cycle ergometers. *Int J Sports Med* 27: 444-447

- Pichot V, Busso T, Roche F, Garet M, Costes F, Duverney D, Lacour JR and Barthelemy JC (2002) Autonomic adaptations to intensive and overload training periods: a laboratory study. *Med Sci Sports Exerc* 34: 1660-1666
- Rietjens GJ, Kuipers H, Adam JJ, Saris WH, van Breda E, van Hamont D and Keizer HA (2005) Physiological, biochemical and psychological markers of strenuous training-induced fatigue. *Int J Sports Med* 26: 16-26
- Rushall BS (1990) A Tool for Measuring Stress Tolerance in Elite Athletes. *Journal of Applied Sport Psychology* 2: 51-66
- Seiler KS and Kjerland GO (2006) Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? *Scand J Med Sci Sports* 16: 49-56
- Short KR and Sedlock DA (1997) Excess postexercise oxygen consumption and recovery rate in trained and untrained subjects. *J Appl Physiol* 83: 153-159
- Stepto NK, Hawley JA, Dennis SC and Hopkins WG (1999) Effects of different interval-training programs on cycling time-trial performance. *Med Sci Sports Exerc* 31: 736-741
- Sugawara J, Murakami H, Maeda S, Kuno S and Matsuda M (2001) Change in post-exercise vagal reactivation with exercise training and detraining in young men. *Eur J Appl Physiol* 85: 259-263
- Urhausen A, Gabriel HH, Weiler B and Kindermann W (1998) Ergometric and psychological findings during overtraining: a long-term follow-up study in endurance athletes. *Int J Sports Med* 19: 114-120
- Uusitalo AL, Uusitalo AJ and Rusko HK (1998) Exhaustive endurance training for 6-9 weeks did not induce changes in intrinsic heart rate and cardiac autonomic modulation in female athletes. *Int J Sports Med* 19: 532-540

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